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A Fuzzy Logic Approach for Daily Site Recording, Schedule Delay Monitoring and Progress Forecasting

By

Adriana V. Ordonez Oliveros ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entiteled **A Fuzzy Logic Approach for Daily Site Recording, Schedule Delay Monitoring** submitted **by Adriana V. Ordonez Oliveros** in partial fulfillment of the requirements for the degree of **Master of Science in Construction Engineering and Management**.

ABSTRACT

This thesis presents a fuzzy logic model that integrates daily site reporting of activity progress and delays with an updating and forecasting system for construction monitoring and control. The model developed assists in the analysis of the subsequent effects that delaying events may have on the project's completion date.

The following components comprise the fuzzy logic model: an as-built database integrated with project scheduling, a procedure to categorize delays, a method to estimate delay durations utilizing fuzzy logic, a technique to derive triangular membership functions, a procedure that updates the schedule, and a procedure that evaluates the effects of delays on the schedule and determines the likely consequences of delays on activity progress.

This thesis makes a contribution in construction delay analysis by developing a fuzzy logic model that provides a flexible and accurate tool that suits the imprecise nature of this field, and is valuable to the construction industry.

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Symbols

R	Fuzzy relation R
Q	Fuzzy relation Q
F	Fuzzy set F
C	Fuzzy set C
D	Fuzzy set D
S	Fuzzy subset S
T	Union matrix T
V	Union matrix V
X	universe X
Y	universe Y
Z	universe Z
s	s-norm
t	t-norm
sup	Supremum
inf	Infimum
p	Number of fuzzy relations
m	Number of delay duration elements
D_D	Delay duration
D_L	Membership function for Large delay duration
D_{VL}	Membership function for Very large delay duration
D_M	Membership function for Medium delay duration

D_S	Membership function for Small delay duration
D_{VS}	Membership function for Very small delay duration
$P(D = z_k)$	Probability of occurrence of the delay duration element z_k
x_i	Element of universe X
y_j	Element of universe Y
z_k	Element of universe Z
μ	Membership value
$\mu_R(x_i, y_j)$	Membership value of element (x_i, y_j) in fuzzy relation R
$\mu_Q(y_j, z_k)$	Membership value of element (y_j, z_k) in fuzzy relation Q
$\mu_{FxC}(x_i, y_j)$	Membership value of element (x_i, y_j) in Cartesian-Product
$\mu_{CxD}(y_j, z_k)$	Membership value of element (y_j, z_k) in Cartesian-Product
$\mu_F(x_i)$	Membership value of element x_i in fuzzy set F
$\mu_C(y_j)$	Membership value of element y_j in fuzzy set C
$\mu_D(z_k)$	Membership value of element z_k in fuzzy set D
$\mu_S(z_k)$	Membership value of element z_k on fuzzy subset S
$\mu_T(x_i, y_j)$	Membership value of element (x_i, y_j) in the fuzzy relation T
$\mu_V(y_j, z_k)$	Membership value of element (y_j, z_k) in the fuzzy relation V
ToV	Composition of fuzzy relations T and V
$\mu_{ToV}(x_i, z_k)$	Membership value of element (x_i, z_k) in the
μ_D	Mean of the delay duration
σ_D	Standard deviation of the delay duration
X	Fuzzy variable X
μ_F	Membership function of fuzzy set F

π_x	Possibility function associated with *X*
μ_i	Membership values of each element i in X
p_i	Probability values of each element i in X
a	Mean value of π-curve
c	Range parameter of π-curve
$\oplus$	Fuzzy addition
Θ	Fuzzy subtraction
$\vee$	Maximum
$\wedge$	Minimum
$m\tilde{a}x$	Fuzzy maximum
$m\hat{i}n$	Fuzzy minimum
x	Activity under analysis
FES_x	Fuzzy early start of activity x
FEF_x	Fuzzy early finish of activity x
FD_x	Fuzzy duration of activity x
p_x	Predecessor activity
FES_p	Fuzzy early start of activity p
FEF_p	Fuzzy early finish of activity p
FD_p	Fuzzy duration of activity p
FS_{px}	Finish to Start lag time from p to x
SS_{px}	Start to Start lead time from p to x
FF_{px}	Finish to Finish lag time from p to x
SF_{px}	Start to Finish lead time from p to x
FLS_x	Fuzzy late start of activity x

FLF_x	Fuzzy late finish of activity x
s_x	Successor activity
FLS_s	Fuzzy late start of activity s
FLF_s	Fuzzy late finish of activity s
FD_s	Fuzzy duration of activity s
FS_{xs}	Finish to Start lag time from x to s
SS_{xs}	Start to Start lead time from x to s
FF_{xs}	Finish to Finish lag time from x to s
SF_{xs}	Start to Finish lead time from x to s
P	Set of predecessors
T_{proj}	Project duration
FI_x	Fuzzy interruption on activity x
A^u	Upper bound trapezoidal fuzzy number A
PLF	Preliminary late finish
PLS	Preliminary late start
FLF^u	Upper bound for the late finish
Y	Fuzzy number Y
T_x	Duration of path X
T_{CP}	Duration of most critical path
C^{FLS}	Fuzzy late start centroid
C^{FES}	Fuzzy early start centroid
C^{FLF}	Fuzzy late finish centroid
C^{FEF}	Fuzzy early finish centroid
T_F	Total float

Abbreviations

PDF	Probability Density Function
FNET	Fuzzy network scheduling methodology
TFN	Trapezoidal fuzzy number
CPM	Critical path method
PM	Possibility Measure
AI	Agreement Index

CHAPTER 1 INTRODUCTION

1.1 Background and Problem Statement

Delays in the completion of construction projects are an unavoidable condition in the construction industry. Different techniques are used by project managers to monitor and mitigate the effects of delays. Effective control techniques should be used to prevent or minimize the resulting delay claim disputes. The primary control technique used by project managers is the construction schedule. Construction schedules are an important part of the management of construction projects, because they are useful in identifying, analyzing and measuring the effects of construction delays.

Once a delay has been experienced on a project activity, the project manager needs to establish the length of the delay and its effect on the work remaining in the schedule. In many instances, even though the project manager is aware of the existence of a problem affecting the progress of an activity, it will rarely be possible to assess or determine accurately its full extent, its probable consequences, and whether or not it is likely to delay the project completion date. If the project manager fails to determine the potential of the problem in question to develop into a delay, the project manager will fail to take the correct measures to minimize or avoid the consequences of the delay. The process of anticipating the likely effects of the delay is highly uncertain due to the associated difficulty in forecasting the extent and the consequences of the expected delay. It follows that project managers must have the appropriate tools to aid them in the process of updating the schedule based on the correct analysis of the delaying events and their effect upon the completion of the project, so that they will be able to react and reschedule the work in order to avoid and minimize delays.

The aim of this thesis is to provide project managers with a tool that is capable of dealing with the uncertainties inherent to the nature of the delay analysis process, and that will act as an early warning system to alert project managers of the new conditions in the schedule. This tool will enable project managers to assess the effects of the delay and make provisions for them. The tool developed in this thesis is based on the techniques of fuzzy logic, and the approach developed by Ayyub and Haldar (1984) to handle the uncertainty associated with delay analysis.

The next logical step after identifying the effects of a delay is to update and modify the schedule to suit the actual circumstances. The impact of the delay needs to be included in the schedule because succeeding activities may be influenced by the delay, and this will ultimately determine the extent to which the delaying event may delay the completion date of the project.

The process of updating the schedule can only be done effectively by incorporating the uncertainties associated with the process of anticipating the effects of the delay in the schedule. An appropriate technique that employs fuzzy set theory to model uncertainty in project network scheduling was presented by Lorterapong and Moselhi (1996). This technique is employed in this thesis for representing fuzzy activity durations and performing network calculations to calculate actual early start and finish times, and thus produce and updated schedule.

The proper updating of the schedule facilitates the process of monitoring the effects of delays, and aids in the planning of the remaining portion of the schedule in a manner that will allow the remaining work to be executed within the available time. The schedule reflecting the actual conditions, plays an important role in the decision making

process of the project manager, when deciding on altering or modifying the logic of the schedule in order to maintain progress and achieve the planned project completion time.

1.2 Purpose of the Study and Expected Contributions

The main objective of this thesis is to develop a fuzzy logic model that integrates the processing of information related to ongoing site work and delays encountered on a daily basis, with an updating and forecasting system, to assist in the analysis of the subsequent effects that delaying events may have on the completion date of the project. In order to achieve this overall objective, this thesis has the following sub-objectives:

1. To create an as-built database with the purpose of integrating daily site reporting with project planning and scheduling, to identify the relevant project information that is important to capture in the as-built database.
2. To compile a standard list of potential causes for construction project delays.
3. To relate the causes of a delay with their corresponding category: excusable noncompensable, excusable compensable, or nonexcusable.
4. To develop a delay impact estimation procedure based on fuzzy logic for determining the anticipated duration of delaying events that impact activity progress.
5. To implement a technique to transform the probability density function (PDF) that represents the delay duration, into a triangular membership function.
6. To develop a method that revises activity durations and increases them by the amount of the delay duration.

7. To present a method that recalculates and updates the schedule in terms of revised fuzzy activity durations, and determines the actual project completion time.
8. To develop a method that identifies which activity delays contribute to the overall project delay, and presents the project manager with the likely consequences of delays on activity progress.
9. To validate the effectiveness of the fuzzy logic model developed, using a case study of an actual project, and performing a sensitivity analysis of the main components of the model.

In the construction management field, fuzzy logic techniques have been used by several researchers for project scheduling and planning; (Ayyub and Haldar, 1984; Lorterapong and Mosheli, 1996; Smith and Hancher, 1989; Wu and Hadripriono, 1994; AbouRizk and Sawhney, 1993); these applications are described in Chapter 2. Until now, fuzzy logic concepts have not been applied to the field of construction delay analysis. The expected contributions of this thesis are to expand previous research on construction delay analysis by developing a model based on the techniques of fuzzy logic. The use of fuzzy logic provides for a flexible and more accurate delay analysis model that suits the imprecise nature of the problem, and can therefore be of value in practice in the construction industry.

1.3 Research Methodology

The topic of this thesis was chosen based on the knowledge and experience that the author gained after being involved in the on-site monitoring of an actual construction project. The first step towards the development of this thesis was to design and create an as-built database for the project. This database was implemented into Microsoft Access, and was used to store daily project information on progress and delays encountered on the construction project. An as-built schedule was derived for the project, and it was compared and analyzed with respect to the as-planned schedule. The results of the analysis showed how the impact of certain unavoidable delays modified the planned progress of project activities, and determined the actual sequence of construction. The analysis of the information collected motivated the idea to develop a tool that could aid project managers to estimate the effects of the delays in the schedule, and to determine the extent to which delays may affect the project completion date.

Once the practical stage of the research concluded, the next step was to design a fuzzy logic model dedicated to construction daily site recording and progress forecasting. A thorough literature review was performed to identify the various techniques employed by construction practitioners to deal with schedule delays. The first step in the development of the fuzzy logic model was the design of a general as-built database intended to store daily project information, and to use this information to categorize delays. The purpose of the database within the fuzzy logic model is to integrate daily site reporting with project scheduling. The information stored in the database is interpreted by the fuzzy logic model to update the schedule in terms of actual start and finish dates. The structure of this database was designed based on the analysis of claims and scheduling literature, and on the field experience acquired after preparing the as-built

database of the case study project previously mentioned. The database integrated with the fuzzy logic model was implemented in Mircrosoft Excel. Lists of potential causes for construction project delays were incorporated into the as-built database. The lists were compiled after the same process of literature review. The fuzzy logic model uses a cause-effect matrix to categorize delays. This tool was implemented after the examination of the literature previously mentioned.

Studies on the use of fuzzy logic applied to construction scheduling were carefully analyzed, to determine the adequate fuzzy logic techniques to be employed in the development of the fuzzy logic model dedicated to construction daily site recording and progress forecasting. The technique proposed by Ayyub and Haldar (1984) to determine activity durations was employed in the fuzzy logic model to estimate delay durations. This technique was implemented in Visual Basic 6.0 in order to program the mathematical calculations required to obtain the delay duration. The transformation proposed by Dubois and Prade (1986), for deriving membership functions from probability density functions (PDF), was used to transform the PDF that represents the delay duration into a triangular membership function. The technique proposed by Lorterapong and Moselhi (1996) was employed in the fuzzy logic model to recalculate and update the schedule in terms of revised fuzzy activity durations. The two latter techniques were implemented in Microsoft Excel.

The study of claims and scheduling literature also served to create a method that determines if the delay that affected a particular activity had the effect of modifying the network logic, and/or if it had the effect of delaying the project completion date. A method to determine the likely consequences of delays on activity progress was also developed. This method may be employed by the user to modify the projected schedule by

accelerating and/or resequencing the activities, so that the overall effect of delays can be minimized. These methods were implemented into Microsoft Excel.

Once the fuzzy logic model was designed, a case study of an actual project was used to test the performance of the model. The starting point of the analysis was the project as-planned schedule. This schedule was sequentially updated each time a delay occurred on a project activity, based on the information contained in the as-built database created for the project. The analysis shows sequentially how the project evolved from the as-planned schedule into the as-built schedule. The as-built schedule derived by the fuzzy logic model coincides with the actual as-built schedule of the project.

A sensitivity analysis was conducted to evaluate the sensitivity of the delay impact estimation procedure to membership values in the definition of the linguistic variables. In order to perform the sensitivity analysis, the estimation of the delay duration of an activity in the case study project was solved again while varying different parameters that affect the performance of the technique. A validation analysis was also performed to compare the results of the procedure for forecasting progress at completion, with the actual results recorded in the as-built database of the case study project. The scheduling computations were performed again using the actual delay durations of the activities. The scheduling results were compared to the results produced by the fuzzy logic model.

1.4 Thesis Outline

The first chapter of this thesis presents the introduction, which includes background information on the uncertainties inherent to the process of forecasting the extent and the consequences of construction delays. This chapter also presents the objectives of this thesis and the methodology followed to accomplish these goals.

The second chapter of this thesis contains a literature review. It describes previous studies in the field of artificial intelligence applied to construction schedule delays. It also describes different applications of fuzzy set theory in construction scheduling and planning. Fuzzy relations and fuzzy numbers, the techniques used in this research, are introduced, as well as some basic concepts used in construction delay analysis.

The third chapter provides a description of the fuzzy logic model developed in this thesis for processing information related to ongoing site work and delays encountered on a daily basis. The different components of the fuzzy logic model are explained, as well as the procedures and the fuzzy set theory techniques employed in each component to model the construction scheduling situation. This chapter also presents the implementation of the computer program to estimate delay durations.

The fourth chapter presents the case study of an actual construction project used to collect the necessary information to test the performance of the fuzzy logic model developed in this research. This chapter includes the description of the case study project and explains how the project data were collected, organized and processed.

The fifth chapter describes the testing of the fuzzy logic model, using the case study project information collected in the fifth chapter. The calculations performed to analyze the project schedule based on the occurrences of delays are described. The results of the model validation are presented.

The sixth chapter presents a sensitivity analysis to evaluate the sensitivity of the delay impact estimation procedure to variations in its components. This chapter also presents a validation analysis of the results of the procedure for forecasting progress at completion.

The seventh chapter presents the conclusions of this research, the contributions made, the limitations of the fuzzy logic model and the recommendations for future research.

Appendix A presents a hypothetical example project with the purpose of illustrating the fuzzy model components and calculations described in the third chapter. The example project is a simplified house construction project and is used to illustrate the methodology employed in each component of the fuzzy logic model.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction and State of The Art

In recent years, attention has been given to studying the nature of disruptions in construction scheduling. Different approaches have been proposed that recognize the causes of delays, update the schedule by including revised durations, and establish the actual project completion time (Battikha and Alkass, 1994). The techniques proposed serve as tools for construction professionals, in order to understand how a project schedule and ongoing project documentation can be used to establish wether a delay occurred, assess the magnitude of the delay, assess the cause of the delay, and identify the delay's impact on the project.

The analysis of the delays generated from specific impacts is usually performed employing project scheduling methods, such as the critical path method (CPM) or bar charts. At the start of the project an as-planned schedule is prepared based on estimates of productivity and sequences of activities, and a time period is established as the project duration. As the job progresses, unexpected delaying events occur that may affect the project completion time. The schedule is updated to reflect the new conditions, and to determine if the delays have affected the project duration. This process is repeated throughout the life of the construction project.

Consequently, an important part of construction scheduling is concerned with the design of techniques that deal with changes in the schedule and the associated time adjustments, whenever delaying events occur during the course of the construction project (Jingsheng et al., 2001).

The main approaches currently used by construction practitioners to analyze construction delays are summarized as follows. The reader may refer to Alkass and Harris (1991) and Trauner (1990) for further details in these techniques. The major drawbacks of these methods are also discussed. The fuzzy logic model created in this thesis attempts to overcome the limitations inherent to the actual methods utilized in construction delay analysis.

- Global Impact Technique: In this technique, all delays that occurred during the construction of the project are plotted on a bar chart. The durations of all delays are added and this value corresponds to the total delay to the project.

- Net Impact Technique: In this technique, the as planned and as-built schedules are plotted on a bar chart in which only the net effect of the delays is included. The difference between the as-planned and as-built schedules corresponds to the total delay to the project.

- Adjusted as-built CPM Technique: In this technique, an as-built schedule is prepared in CPM format. Delays are included in this schedule as activities linked to the activities that experienced the delays. The difference between the as-planned completion date and the adjusted as-built completion date corresponds to the total delay to the project.

- ‘But for” or collapsing Technique: This technique employs CPM calculations, and entails the owner and the contractor independently, to use the as-planned schedule as a starting point and include in it all delays that each party is willing to accept responsibility for.

2.2 Previous Studies on Construction Schedule Delays

Most research applications in the area of schedule delays are directed to the development of computer-based systems for delay analyses. Battikha and Alkass (1994) developed an integrated computer system for construction delay analysis. The integrated system contains three major components: a project management software, a database management software, and an expert system. The user's function is to input project activity data, which is used by the system to update the as-planned schedule and to determine an actual as-built schedule. The database management software is used by the user to record project information. The project management software transfers information to and from the database software, by exporting and importing information. The expert system component contains a knowledge base on construction delays to predict the type of delay as excusable compensable, excusable noncompensable, or nonexcusable.

Alkass and Harris (1991) presented an integrated system that aids in the analysis of claims resulting from delays occurring on construction projects. The Computerized Delay Claims Analysis (CDCA) uses existing software such as project management and database management. In addition to these, it uses an expert system containing experimental knowledge and engineering judgement to facilitate the decision making process during claim analysis. The delay-expert system identifies potential entitlement issues from given facts, and provides legal guidance on the procedures for the presentation of claims arising. A probable prediction of the final outcome regarding entitlement is also presented.

Yates (1993) presented a Project Management Knowledge Engineering System (PMKES) for assessing possible causes for project delays and presenting alternative

suggestions and recommendations as to how prevent additional delays. The PMKES system also monitors the progress of a project towards achieving project milestones, and provides an accurate evaluation of project performance. The computer system determines delay by comparing technical parameters and accessing the knowledge base that contains knowledge of experts in the field of project controls. The data generated by the PMKES system is used in scheduling control.

Conlin and Retik (1997) identified the techniques used in the construction industry for monitoring and minimizing the effects of delays. They establish how these techniques could make use of both the current computer technology and advanced artificial intelligence tools, such as knowledge-based expert systems and visualization techniques.

Project documentation plays an important role in computer-aided construction delay analysis systems. Adequate project documentation is necessary when performing a delay analysis, in order to determine relevant delay information. For this reason, as-built databases are integrated with computer based systems, to store information on each delay as it occurs. The systems maintain as-built databases so that whenever delay information is required, it can be easily retrieved, thereby eliminating the need to sift through the various sources of project documentation. As-built databases are linked to expert systems to ascertain the contractor's entitlement for any extension of time and/or damages. The information contained in the as-built databases is also linked to scheduling systems, so that it is possible to establish as-built schedules (Battikha and Alkass, 1994).

Russell (1993) highlighted the importance of automating daily site records, and integrating the collection of field data with a planning and scheduling system. Russell

developed a computerized daily-site reporting system for collecting and processing site information that improves the process of recording field data, allows a faster response to problems, and is helpful in dealing with claims.

2.3 Categories of Construction Delays

Construction delays and their classification have been discussed in the literature (Trauner 1990; Rubin, 1999; Carnell, 2000; Alkass et al., 1991, 1996). Generally they are classified according to liability into two major types, namely excusable or nonexcusable delays.

Excusable delays are those not attributable to the contractor's actions or inactions, and typically include unforeseen events. These events are beyond the contractor' s control and are without fault or negligence on his/her part. Excusable delays, when founded, entitle the contractor to a time extension if the completion date is affected. Excusable delays can be further classified into compensable and noncompensable delays.

Excusable compensable delays are caused by the owner' s actions or inactions. When contractors encounter this type of delay, they are entitled to a time extension as well as monetary compensation due to the delays.

Excusable noncompensable delays are delays where neither the owner nor the contractor is deemed responsible. When this type of delay is encountered, only a time extension is warranted since there are no grounds for damages. Some examples of excusable noncompensable delays are unprovoked strikes, or any 'Act of God'.

Nonexcusable delays result from the contractor's or sub-contractor's actions or inactions. Consequently, this type of delay presents no entitlement to a time extension or

delay damages for the contractor, if the delay can be proven to have affected the whole project. The owner, however, could be entitled to liquidated damages.

Concurrent delays refer to delay situations when two or more delays occur at the same time or overlap to some degree. If either delay had occurred alone it would still have affected the project completion date (Rubin, 1999).

2.4 Schedules Used in Delay Analysis

Different versions of construction schedules are used in delay analysis. The different types of schedules are summarized here.

2.4.1 As-Planned Schedule

The as-planned schedule represents the contractor's original plan for completing the work. It depicts the contractor's planned construction sequences prior to the occurrence of any schedule impact or project delays. The activity durations and work sequences of the contractor's as-planned schedule should be reasonable, feasible and consistent with the manpower and equipment resources assumed in the bid. The logical activity relationships should be based upon physical constraints and normal construction sequences (Battikha and Alkass, 1994; Trauner, 1990).

2.4.2 As-Built Schedule

During the project life the as-planned schedule should be updated on a regular basis and whenever important events happen. The actual start and finish dates of the activities, remaining durations, delays, and in some cases changes in logic should be

incorporated, so it progressively becomes the as-built schedule at the completion of the project.

An as-built schedule documents how a project was built over time. It indicates the actual start and end dates of each activity during the construction, periods of no progress, and activity dependencies and relationships. It depicts the actual sequence of activities as they occurred during the entire project. The critical path(s) and the project start and finish dates may be different than that of the as-planned schedule.

This schedule is often used to evaluate delay and/or disruption claims. The as-built schedule is often compared to the as-planned schedule to indicate the variations, the extended durations, and the late starts and finishes of the different activities. (Battikha and Alkass, 1994; Trauner, 1990).

2.4.3 As-Built Database

An as-built database is derived directly from the different sources of project documentation. The as-built database provides a record of daily project progress, and a detailed status of project activities. The information recorded in the database correctly reflects actual construction sequences between project activities, and the actual timing of activities. The as-built database constitutes the basis for the preparation of the associated as-built schedule. The information contained in the as-built database can be used to support the analysis of delay claims (Knoke and Jentzen, 1994, 1996).

2.5 Application of Fuzzy Set Theory in Construction Scheduling

Different techniques are available for the estimation of activity durations in project planning and scheduling. Construction engineers employ techniques such as the critical path method (CPM) or program evaluation review technique (PERT). The information used in these techniques is often nondeterministic in nature. Fuzzy sets are a useful tool in solving many problems in construction scheduling, such as the estimation of activity durations, when the baseline information is not known with certainty (Ayyub and Haldar, 1984).

In 1965, Zadeh introduced the concept of fuzzy set theory (Zadeh, 1965). Applications of fuzzy set theory in various fields have indicated that fuzzy sets are a useful tool for providing significant solutions to complex real-world problems. The analysis of complex problems can be approached by describing the problem by means of subjective judgements. Experienced engineers can produce these subjective judgements, which can be analyzed as linguistic variables. The meaning of the linguistic variables can be interpreted numerically with the use of membership functions. Fuzzy sets provides the mathematical background to manipulate the membership functions in order to obtain significant answers to an initially complex problem (Brown and Yao, 1983).

Construction engineers frequently determine activity durations based on judgment, and on their past experience in performing similar activities. The associated uncertainties in the level of experience and judgment have substantial impacts on the estimation of the duration of construction activities, and on network calculations. Determining an accurate activity duration estimate is necessary because all subsequent calculations of the scheduling process are based on the assumption that the duration of each activity is correctly estimated. (Ayyub and Haldar, 1984).

Construction projects are usually characterized by many factors that may have an impact on the normal progress of project activities. Various studies have documented the use of fuzzy sets for estimating the durations of project activities, taking into account factors such as site condition, weather, labour performance, etc., which are expressed in linguistic terms (Ayyub and Haldar, 1984; Smith and Hancher, 1989; Wu and Hadripriono, 1994; AbouRizk and Sawhney, 1993).

Ayyub and Haldar (1984) considered it necessary to include the impact of these factors whenever construction engineers assess activity durations. The factors that can affect the duration of an activity are usually expressed in linguistic values, rather than numerical values. In the technique proposed by Ayyub and Haldar, the effects of qualitative factors are modeled mathematically using fuzzy sets, for estimating the mean and variance values of an activity's duration.

Smith and Hancher (1989) proposed a fuzzy logic technique for estimating precipitation impacts for scheduling. Fuzzy sets are employed as a method for quantifying qualitative variables related to the impact of precipitation disruptions on activity durations, for scheduling purposes. Estimates of precipitation impacts are obtained by identifying linguistic variables for time impacts related to precipitation events.

The technique proposed by Wu and Hadripriono (1994) uses fuzzy sets to estimate the duration of construction activities. A model, Activity Duration Decision Support System (ADDSS), employs the Fuzzy Modus Ponens Deduction (FMPD) technique to evaluate the impact of different factors on activity duration. The FMPD technique converts qualitative expressions used to assess these factors into numerical values using Angular Fuzzy Set Theory.

AbouRizk and Sawhney (1993) adapted the method proposed by Ayyub and Haldar (1984) in the development of a computer system called "SIDES". The input data include the factors that affect the activity duration, and their respective likelihood of occurrence and adverse consequences on the activity being considered. The outputs of the system are the mean and variance values of the duration, and the shape parameters of the beta distribution from subjective data provided by the users.

A significant application of fuzzy sets for estimating the durations of project activities is the fuzzy network scheduling method (FNET) proposed by Lorterapong and Moselhi (1996). The FNET technique models the uncertainties associated with the statements used by experts in estimating activity durations. The proposed quadruple form of the trapezoidal distribution efficiently models various degrees of uncertainties related to the estimation of activity durations. Other capabilities of this technique include the calculation of scheduling parameters and the interpretation of the fuzzy results generated.

Various applications in the civil engineering field include the use of subjective information to asses practical problems, analyzed by means of fuzzy set theory. Ayyub and Haldar (1986) presented a method for selecting the most desirable construction strategy based on subjective information describing the factors that affect the safety of construction operations. Yao (1980) presented a model that applies fuzzy set theory to the problem of damage assessment of existing structures. This approach uses fuzzy relations to identify structural damage. Brown and Yao (1983) reviewed various applications of fuzzy set theory in structural engineering, and proposed a method that uses subjective arguments to asses the concrete stress of structural members. Brown

(1979) presented a model for obtaining a safety measure that includes the analysis of linguistic estimates of subjective information.

Fuzzy set theory has been used in diverse construction management applications. Russell and Fayek (1994) developed an automated corrective action selection system that assists in the selection of corrective actions when problems arise on the construction site. Elton et al. (1994) presented a model to aid in contractor pre-qualification. Fayek (1998) utilized fuzzy set theory to set a mark-up for bidding on construction projects. Nguyen (1985) applied fuzzy sets to tender evaluation.

2.6 Fuzzy Relations

Fuzzy set theory is used in the model developed in this thesis for assessing the schedule impact of delays on a construction project. The relevant aspects of fuzzy set theory are discussed below.

A crisp relation designates the presence or absence of association or interaction among the elements of two sets. A crisp relation assigns a value of 1 to every element that belongs to the relation, and 0 to every element that does not belong to it. Fuzzy relations generalize the concept of crisp relation, to allow the notion of partial degrees of membership or strengths of association, between the elements in the universe of discourse. A fuzzy relation can be represented as a fuzzy set on the Cartesian product of crisp sets $X_1, X_2, \ldots, X_n$, where tuples $(x_1, x_2, \ldots, x_n)$ may attain different grades of membership within the relation. The degree of membership denotes the strength of association between the elements of the tuple (Klir and Yuan, 1995).

Fuzzy relations can be used in describing the relationships between linguistic terms (Pedrycz and Gomide, 1998). If two sets are involved, the relationship is called

binary. Binary relations represent the relationship among two data sets by the grade of association between the sets. A binary relation is a set itself; for this reason, basic fuzzy set operations can be applied to a binary relation such as union, intersection and complement. Mathematical operations such as the inverse and composition can also be performed on binary relations. A useful representation of fuzzy binary relations is a membership matrix, where the values of the matrix denote the values of the degree of membership among the sets. Binary relations may also be represented using sagittal diagrams and directed graphs (Klir and Yuan, 1995).

2.7 Fuzzy Numbers

Fuzzy numbers can be used to represent imprecise quantities such as "numbers that are close to a given real number" or "numbers that are around a given interval of real numbers" (Klir and Yuan, 1995). Examples of imprecise quantities are "about ten", "approximately five" or "below twenty". Fuzzy numbers are fuzzy sets defined on the set *R* of real numbers. A fuzzy number is a continuous fuzzy set that possesses the properties of normality and convexity. The fuzzy set must be normal to ensure that the most definitive possible value in the set has a membership grade of 1. The concept of a set of "real numbers around *x*" must be fully satisfied by element *x* itself, hence its membership grade must be 1. The fuzzy number is a convex fuzzy set to ensure that the membership function has one evident peak (Lorterapong and Moselhi, 1996).

2.8 Possibility Theory

The possibility of an event denotes a subjective judgment related to the possibility of occurrence of that event (i.e. a number that represents someone's perception about

this possibility, when responding to the question "may this event occur?") (Dubois and Prade, 1986).

The mathematical background of fuzzy sets provides a foundation for possibility theory. A fuzzy variable is related with a possibility distribution in the sense that the membership function of the fuzzy variable may be interpreted as a possibility distribution. (Zadeh, 1978). Zadeh (1978) stated the relation between fuzzy variables and possibility distribution functions, as follows:

Let *X* represent a variable that takes values in the universal set X, and let the equation $X = x$, where $x \in X$, be employed to describe the fact that the value of *X* is x. Let *F* be a fuzzy subset of X which is characterized by its membership function μ_f, with the grade of membership $\mu_f(x)$ interpreted as the degree of compatibility of x with the concept described by *F*. The possibility function associated with *X* is denoted by π_x and is defined to be numerically equal to the membership function of *F*. Thus, $\pi_x(x)$, the possibility that $X = x$, is numerically equal to $\mu_f(x)$, the degree to which x belongs to *F*:

$$\pi_x(x) = \mu_F(x) \tag{2-1}$$

As an example, let the variable *X* represent the duration of an activity measured in days and assume that it only takes values in the set Z of all integers (i.e. $X = Z$). Let data about the actual value of *X* be given in terms of the proposition "*X* is about 20 days" where the concept “about 20 days” is expressed by the fuzzy set *F* shown in Figure 2.1. This incomplete information generates a possibility distribution function π_x that according to equation (2-1), is numerically equal to the membership function of *F*.

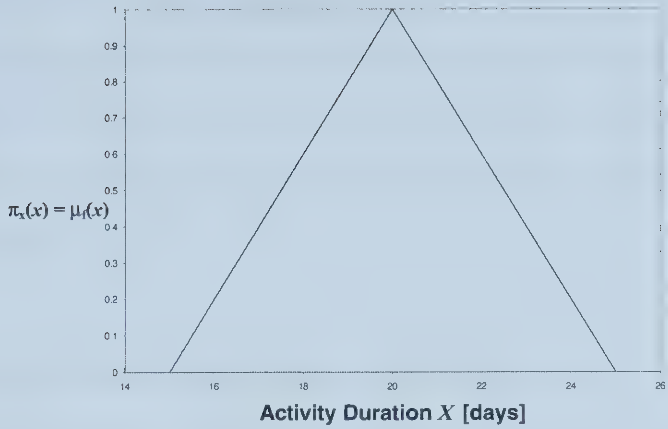


Figure 2.1 Possibility distribution and membership function for variable X

2.8.1 Consistency between Possibility and Probability Theories

Probability theory is represented by probability density functions, and possibility distribution functions or membership functions represent possibility theory. The normalization requirement for a probability density function establishes that the area under this curve is 1. The normalization requirements for a possibility distribution function or a membership function of a fuzzy set, establishes that the largest membership grade obtained by an element in that set is required to be 1 (Klir and Yuan, 1995).

It has been established that possibility theory provides the basis for a connection between fuzzy sets and probability theory. (Klir and Yuan, 1995). The consistency between probability and possibility theories was suggested by Zadeh (1978). Dubois and Prade (1986) stated that if the possibility of occurrence of events is reduced, their probability of occurrence is reduced as well; likewise if the tendency of occurrence of events is enhanced, their probability of occurrence tends to increase. The concept of

possibility theory entails a relationship formulated by Zadeh (1978), known as the consistency principle: "what is possible may not be probable and what is improbable need not to be impossible." This statement was interpreted by Pedrycz and Gomide (1998), as follows: "the degree of possibility (membership) of a certain element is greater than or equal to its probability".

2.8.2 Probability and Membership Functions Transformations

Probability and possibility transformation have been studied to comprehend the relationship between the two theories, and also to solve practical problems such as constructing a membership function of a fuzzy set from statistical data (Klir and Yuan, 1995).

To deal with this problem, a bijective transformation was proposed by Dubois and Prade (1986), for deriving grades of possibility from a probability distribution obtained from a histogram. The possibility-probability transformation suggested by Dubois and Prade is as follows:

Consider a finite universe given by,

$$X = \{x_1, x_2, \ldots, x_n\} \tag{2-2}$$

Let membership values of each element i in X be represented by,

$$\mu = \mu(x_i) = \{\mu_1, \mu_2, \ldots, \mu_n\} \tag{2-3}$$

Where i denotes the i-th element between 1 and n

Let probability values of each element i in X be represented by,

$$p_i = p(x_i) = \{p_1, p_2, \ldots p_n\} \tag{2-4}$$

Assume that the elements of X are ordered in such a way that the membership and probability values are always in nonincreasing sequences. That is,

$$\mu_i \geq \mu_{i+1} \tag{2-5}$$

$$p_i \geq p_{i+1} \tag{2-6}$$

It is required that:

$$\mu_1 = 1 \tag{2-7}$$

$$\sum_{i=1}^{n} p_i = 1 \tag{2-8}$$

The respective membership values μ_i are determined as:

$$\mu_i = \sum_{j=1}^{n} \min(p_i, p_j) \tag{2-9}$$

Where j is the summation index

The transformation leading to the probability function is inferred from (3-53):

$$p_i = \sum_{j=1}^{n} \frac{(\mu_j - \mu_{j+1})}{j} \tag{2-10}$$

Equations (2-9) and (2-10) define a mapping from the set of possibility distributions μ_f over X, into the set of probability densities p, and vice versa. A noticeable feature of this mapping is that the probability density function and the membership function have the same shape. This indicates that the shape of the membership function obtained from the transformation given in equation (2-9), is bell-shaped. The next section examines some characteristics of the bell-shaped membership function and describes how it is transformed into a triangular membership function.

2.8.3 The Bounded Bell-Shaped Membership Function

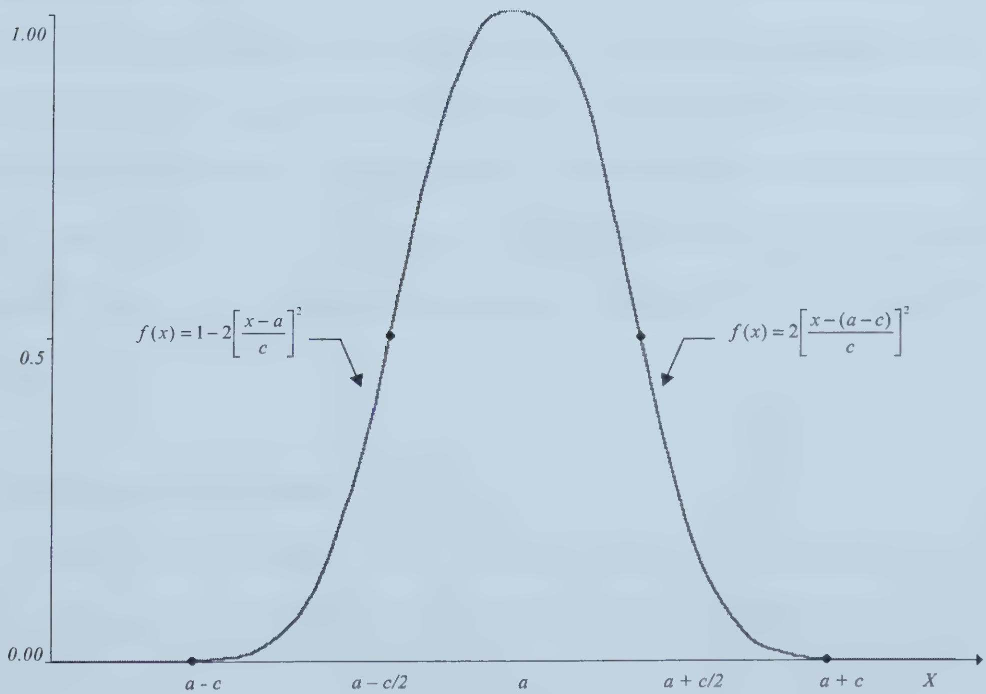


Figure 2.2 Typical π-curve membership function

The bounded bell-shaped function has been used as a membership function to represent fuzzy numbers (Elton et al., 1994, Juang et al., 1992). The bounded bell shaped function is also known as π-curve, and it is defined in Figure 2.2. The π-curve has two important characteristics: it is symmetric in shape, and the area under the curve is one half of the range over which the function is defined. Since the curve represents a membership function, the maximum membership grade is 1, and it occurs at the center of the range. An important feature of a π-curve is that the membership grade at the midpoint between the center and the lower (or upper) bound of the range is 0.5. The range reflects the degree of fuzziness or uncertainty about its most credible value, which is located at the center of the range. By determining appropriate range parameters a and c, the π-curve membership function is completely defined. Parameter a corresponds to the mean or most credible value. Parameter c is determined by calculating the area under the membership function that corresponds to the maximum value of the cumulative function (Elton et al., 1994). In the case of the fuzzy logic model, the X-axis represents the values of the delay duration, and parameter a corresponds to the mean delay duration.

2.9 Trapezoidal fuzzy numbers

A trapezoidal fuzzy number (TFN) is shown in Figure 2.3. The quadruple (a, b, c, d) defines a trapezoidal fuzzy number. The values a and d correspond to the lower and upper bounds. The values b and c correspond to the lower and upper modal values.

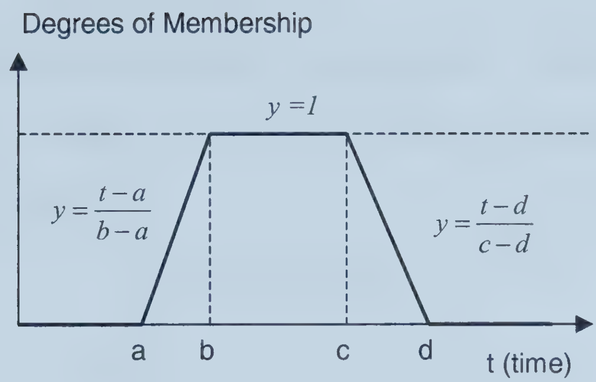


Figure 2.3 Trapezoidal fuzzy number (Lorterapong and Moselhi,1996)

A triangular fuzzy number can be obtained when the lower and upper modal values of a TFN are equal (i.e. $b = c$). Figure 2.4 depicts a triangular fuzzy number.

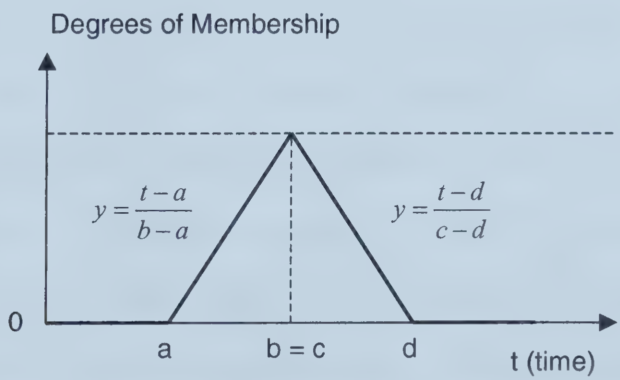


Figure 2.4 Triangular fuzzy number (Lorterapong and Moselhi,1996)

Figures 2.3 and 2.4 show the membership functions of each TFN. The amount of the left spread, the middle plateau, and the right spread indicate together, the degrees of fuzziness or uncertainty related with each TFN.

2.9.1 Fuzzy Times

In the crisp state, the most precise form of time in which a single value of time, t_1, is known with certainty, is shown in Figure 2.5. The grade of membership of the time element can be either 1.0 or 0.

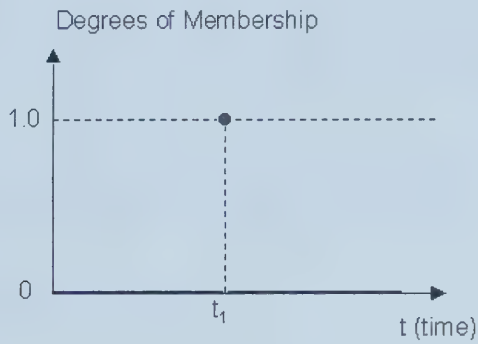


Figure 2.5 Crisp Time (Lorterapong and Moselhi,1996)

In the fuzzy state, fuzzy times can be generated by assigning degrees of membership values from 0 to 1, thus permitting a transition from membership to nonmembership. Figures 2.6 to 2.8 depict representations of fuzzy times. The triangular distribution shown in Figure 2.6 illustrates the case in which the most credible time is t_2, but the time may assume any value between t_1 and t_3. Figure 2.7 shows the time that takes place definitely after t_4 and, most possibly, after t_5. This case is referred as the fuzzy lower bound. Figure 2.8 depicts the time that takes place most possibly before t_7 and, definitely, before t_6. This case is referred as the fuzzy upper bound.

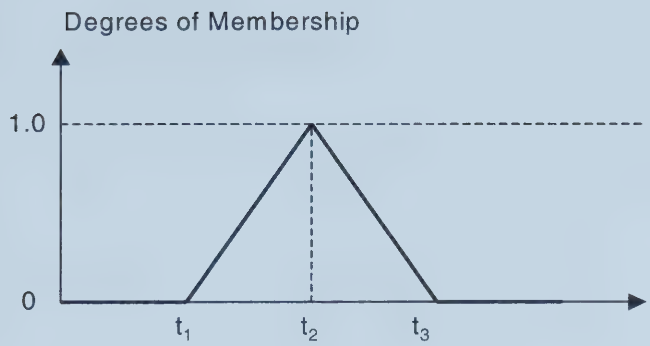


Figure 2.6 Triangular distribution. (Lorterapong and Moselhi,1996)

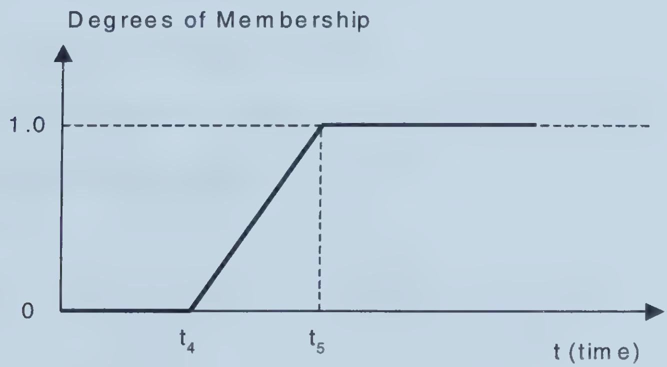


Figure 2.7 Lower bound. (Lorterapong and Moselhi,1996)

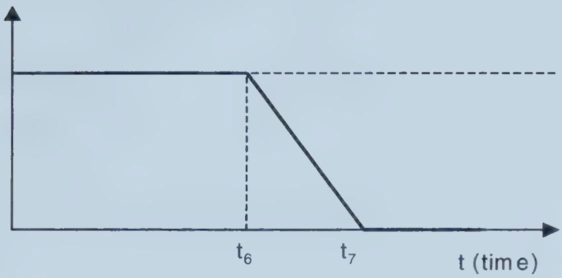


Figure 2.8 Upper bound. (Lorterapong and Moselhi,1996)

2.9.2 Operations on Trapezoidal Fuzzy Numbers

The following are operations on fuzzy numbers that Lorterapong and Moselhi (1996) employed in their proposed method:

Let $M = (a_1, b_1, c_1, d_1)$ and $N = (a_2, b_2, c_2, d_2)$ be any two TFN's, then:

$$M \oplus N = (a_1 + a_2, b_1 + b_2, c_1 + c_2, d_1 + d_2) \tag{2-11}$$

Where $\oplus$ = Fuzzy addition

$$M \ominus N = (a_1 - d_2, b_1 - c_2, c_1 - b_2, d_1 - a_2) \tag{2-12}$$

Where θ = Fuzzy subtraction

$$\tilde{\max}(M,N) = [\vee(a_1,a_2)\vee(b_1,b_2),\vee(c_1,c_2)\vee(d_1,d_2)] \quad (2\text{-}13)$$

Where $\tilde{max}$ = Fuzzy maximum

$\vee$ = Maximum

$$\tilde{\min}(M,N) = [\wedge(a_1,a_2)\wedge(b_1,b_2),\wedge(c_1,c_2)\wedge(d_1,d_2)] \quad (2\text{-}14)$$

Where $\tilde{min}$ = Fuzzy minimum

$\wedge$ = Minimum

2.9.3 Possibility Measure

The possibility measure is used to determine the extent to which two fuzzy sets *A* and *H* overlap (Pedrycz, 1998). The possibility measure Poss (*A, H*) of a fuzzy set *H* with respect to *A*, is defined as follows:

$$Poss(A,H) = \sup_{x\in X}[\min(A(x),H(x))] \quad (2\text{-}15)$$

Where sup = Supremum

min = Minimum

The FNET method uses the possibility measure (PM) for evaluating the degree of overlap of a fuzzy number to another. Figure 2.9 shows two triangular fuzzy numbers *A* and *H*. The possibility measure of these two fuzzy numbers corresponds to the value of the maximum membership grade of the elements that are common to *A* and *H*.

Graphically, the possibility measure can be determined as the highest point in the intersection area produced by the two numbers (Lorterapong and Moselhi, 1996). In this case the PM is calculated to be 0.84.

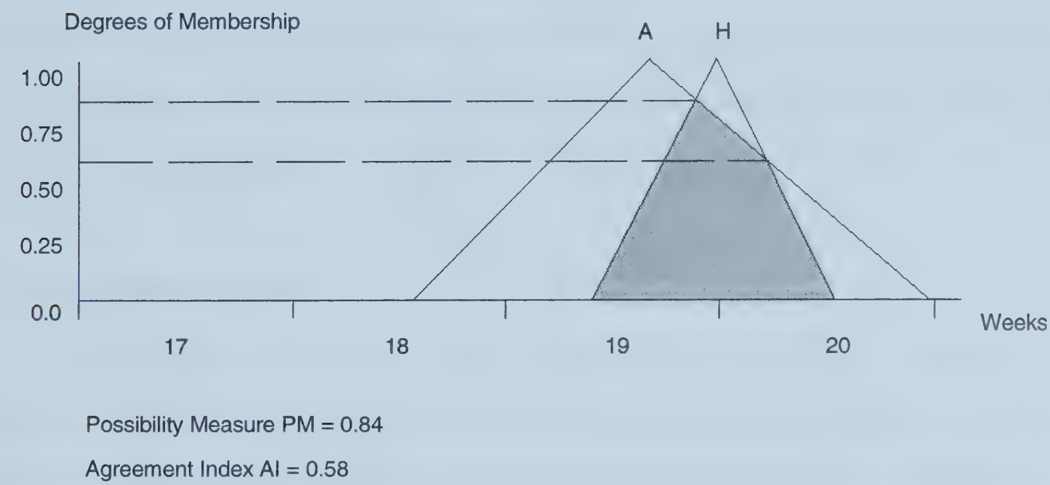


Figure 2.9 Possibility Measure and Agreement Index - First case

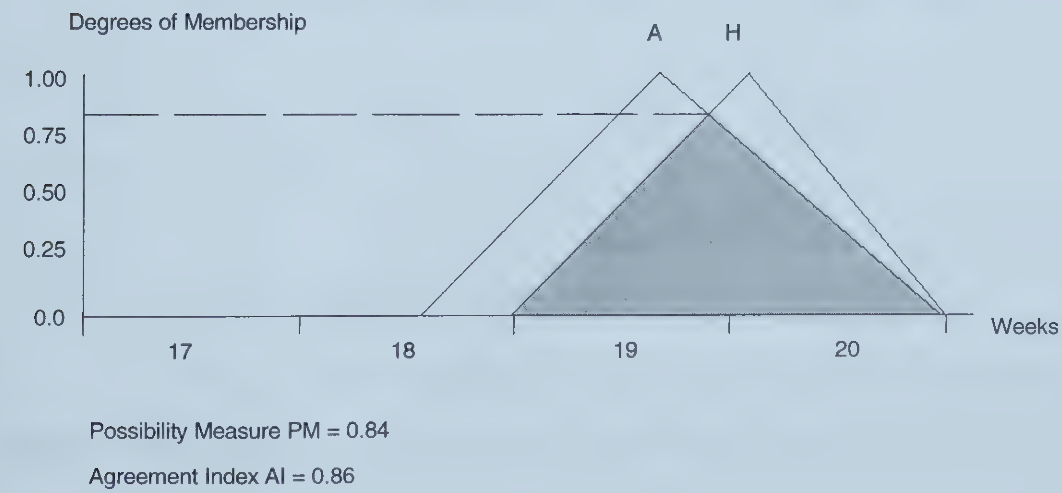


Figure 2.10 Possibility Measure and Agreement Index - Second case

The possibility measure determines the maximum point in the intersection area of two fuzzy numbers. However this value does not take into account the size of the intersection area. Figures 2.9 and 2.10 illustrate two cases where the PM are equal. (i.e. PM = 0.84). However, in the case shown in Figure 2.10, the two fuzzy numbers are more in agreement with each other than the fuzzy numbers of the first case shown in Figure 2.9. Lorterapong and Moselhi (1996) considered that determining the degree of compatibility of a fuzzy number to another using the PM alone is inadequate.

2.9.4 Agreement Index

Lorterapong and Moselhi (1996) implemented in their FNET technique the agreement index (AI) introduced by Kaufmann and Gupta (1985). The PM and AI can be used as complementary tools to determine the compatibility of two fuzzy numbers. The AI measures the ratio of the intersection area between two fuzzy numbers (i.e. shaded area in Figures 2.9 and 2.10), and the entire area of the base or reference fuzzy number (i.e. area of fuzzy number A). The agreement index, $AI\ (A,\ H)$ of A with respect to H is defined as:

$$AI(A,H) = \frac{(areaA \cap H)}{areaA} \tag{2-16}$$

Where $\cap$ represents the intersection area

In the first case shown in Figure 2.9, the AI of fuzzy numbers A and H is calculated using equation (2-16) to be 0.58. In the second case shown in Figure 2-10, the AI of the two numbers is 0.86. These results imply that the numbers in the second case are more compatible with each other than the numbers in the first case.

2.10 Summary

Most research applications used in the construction industry for monitoring and minimizing the effects of delays make use of current computer technology and artificial intelligence tools, such as knowledge based expert systems (KBES) for delay analysis. Most applications of KBES's in the field of schedule delays are concerned with delay claims analysis. The domain of knowledge of these expert systems is directed towards analyzing disputes that arise due to different categories of delays, and determining the responsibility of each party. Other KBES's are applied to construction scheduling, which make use of network scheduling tools to quantify and analyze the causes of schedule delays.

All civil engineering fields have already been influenced, to various degrees, by the new alternatives opened up by fuzzy set theory to approach engineering problems. The many applications of fuzzy set theory in construction management have proven the usefulness of fuzzy set theory in solving practical problems. The utility of fuzzy set theory has been recognized in construction scheduling. Different studies have explored successfully the potential of fuzzy sets for dealing with a variety of specific problems in this domain. This chapter examined some representative problems in construction scheduling in which the appropriateness of fuzzy sets is now well acknowledged.

The unique nature of the construction projects in civil engineering creates a specific degree of uncertainty in every project, in the sense that the available information concerning past projects never fully fits the circumstances of the actual project. As a consequence, there can be significant uncertainty in applying existing information and past experience to new construction projects. The manner that the construction engineer deals with this uncertainty is crucial due to the associated risk of every construction

project. The construction engineer has to make decisions despite the great uncertainty that he or she faces.

Decisions in construction management are usually made by subjective judgments based on past experience, previous knowledge of similar projects, and "rules of thumb" created by accumulating that experience and knowledge. In spite of the technology now available, great uncertainty concerning the application of this knowledge to actual construction projects is still a reality, due to the uniqueness of each construction project, and because the use of subjective judgments and "rules of thumb" is unavoidable. For this reason, construction engineers have found in fuzzy set theory a valuable tool in solving construction management problems.

CHAPTER 3 A FUZZY LOGIC APPROACH FOR DAILY SITE RECORDING, SCHEDULE DELAY MONITORING AND PROGRESS FORECASTING

3.1 Introduction

This chapter describes the fuzzy logic model for processing information related to ongoing site work and delays encountered on a daily basis. It integrates daily site recording with an updating and forecasting system and with the development of a standard classification of delaying contributors that affect activity progress.

The purpose of this fuzzy logic model is to assist in the analysis of the subsequent effects that delaying events affecting the normal progress of an activity, may have on the completion date of the project.

3.2 Overview of the Fuzzy Logic Model

The fuzzy logic model is comprised of the following components that are described in detail in following sections. Figure 3.1 is a flowchart that summarizes all fuzzy logic model components and their respective sections within this chapter. The first component of the fuzzy logic model involves the daily recording of progress information in the as-built database, as well as information related to delays. The second component of the fuzzy logic model categorizes delays by utilizing a cause/effect matrix that relates the causes of delays with the corresponding party responsible for them. The third component estimates delay durations utilizing fuzzy sets and fuzzy relations. The fourth component transforms delay durations into triangular fuzzy numbers. The fifth component increases original activity durations by the amount of the delay. The sixth component recalculates and updates the schedule in terms of fuzzy early and late times, and determines a new

actual project completion date. The seventh component evaluates if the delays have the effect of altering the project completion date. Finally, in the eighth component, the user may modify the projected schedule by accelerating and/or resequencing the activities, so that the overall effect of delays can be minimized.

3.3 Use of Daily Site Records to Generate an As-Built Database

The first component of the fuzzy logic model is the creation of an as-built database. An as-built database documents activity progress on a daily basis. A precise picture of daily progress on activities is derived directly from project documentation, and it accurately reflects project timing, sequence, and progress. (Russell, 1993). The as-built database proposed in this fuzzy logic model was created with the purpose of integrating daily site reporting with project planning and scheduling. Once the user enters the information into the as-built database, the daily data contained in it can be interpreted to update the schedule in terms of actual start and finish dates. This schedule can be used to plan future work based on actual performance, delays encountered and schedule changes in the plan.

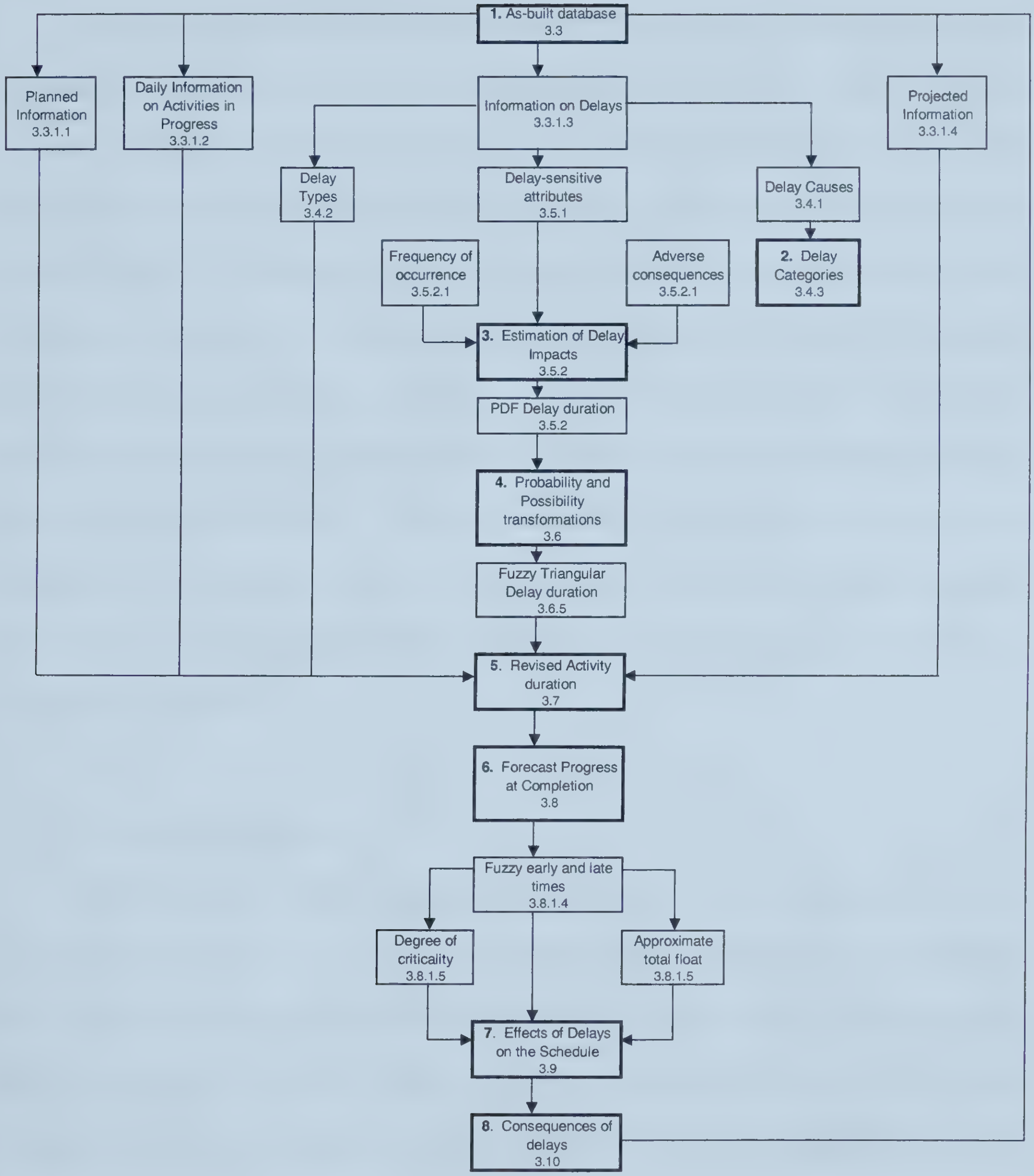


Figure 3.1 Flowchart of the Fuzzy logic model

3.3.1 Information in the Database

Figure 3.2 shows a sample of the database record used in the fuzzy logic model. The information to be included in the database was selected based on field experience and after a thorough examination of claims and scheduling literature (Conlin and Retik 1997; Knoke and Jentzen, 1994; Knoke and Jentzen, 1996; Rubin 1999; Russell 1993; Zartab, 1996). The database contains four sections as follows: planned information, daily information on activities in progress, information on delays, and projected information. Daily information on activities is necessary to identify the state of each activity on a daily basis. The information on delays is helpful in explaining reasons behind the current status of activities and of the project. Projected information includes actual performance that incorporates the impacts of delays in the schedule. A comparison between projected information and planned information is essential to explain causes and deviations of planned performance.

3.3.1.1 Planned Information

The first section of the database contains information related to the original plan for completing the work. It includes the planned activity durations and work sequences prior to the occurrence of any schedule impact or project delays. The user inputs information related to the activity planned duration, and its planned early and finish times. The user then indicates whether the activity is critical on non-critical by entering "yes" in front of the respective option. After that, the user writes the name of the predecessor or successor activities and enters the corresponding relationship with respect to the activity under consideration. (i.e., start-to-start = 12, finish-to-start = 0).

DATABASE RECORD
PLANNING AND SCHEDULING INFORMATION

1. PLANNED INFORMATION

ID __________
Activity __________
Original Duration __________
Planned early start __________ *Planned early finish* __________
Planned late start __________ *Planned late finish* __________
Critical __________ *Non-critical* __________
Predecessor __________ *Relationship* __________
Successor __________ *Relationship* __________
Planned Total Float __________

2. DAILY INFORMATION ON ACTIVITIES IN PROGRESS

Date
Weather __________
Work scope completed __________
Description of work in progress __________
Actual status (Postponed, Started, Ongoing, Idle, Finished) __________
Trade Responsible __________

3. INFORMATION ON DELAYS

Date of occurrence __________
Description of delay __________
Causes of delay __________
Party responsible __________
Type of delay __________
Delay-sensitive attributes __________
Duration of delay __________
Category of delay __________

4. PROJECTED AND AS-BUILT INFORMATION

Actual Duration __________
Actual early start __________ *Actual early finish* __________
Actual late start __________ *Actual late finish* __________
Critical __________ *Non-critical* __________
Actual Predecesor __________ *Relationship* __________
Actual Succesor __________ *Relationship* __________
Actual Total Float __________

Figure 3.2 Database Record

3.3.1.2 Daily Information on Activities in Progress

The second section of the as-built database stores information related to activity progress on a daily basis, documenting the current status of activities in terms of activity state (e.g. postponed, started, ongoing, idle or finished), work scope completed, description of the work performed, daily weather and trade responsible for the activity.

3.3.1.3 Information on Delays

The third section of the database includes data concerned with delaying events that affect normal activity progress such as: date of occurrence, description of the delaying event, the construction party responsible for the delay, delay type, specific causes that generated the delay, delay-sensitive attributes that determine the activity's sensitivity to different causes of delays, delay duration, and delay category.

Causes and types of delays are explained in more detail in the next sections. Section 3.4.3 depicts the methodology used to determine the delay category. Section 3.5 contains a description of the purpose of delay-sensitive attributes and how delay duration is determined.

3.3.1.4 Projected and As-Built Information

During the project life, the as-built database should be updated by the user on a regular basis and whenever important events occur. This section of the database contains the actual start and finish dates of the activities, remaining duration, and changes in logic. Section 3.8 explains the procedure utilized in this fuzzy logic model to update the schedule. After each update, the projected information progressively becomes the as-built information as the project nears completion.

3.4 Delay Causes, Types and Categories

3.4.1 Delay Causes

Although it may be complicated to determine the causes of a delay, there are many ways that a construction project can be delayed. The circumstances that can affect the normal execution of a construction project may result from the direct actions or inactions of any or all parties to the design and construction process. Additionally, outside forces and parties may interfere to delay the project. This component of the fuzzy logic model determines the causes of delays by looking at the responsibility of the main parties in the construction project: the owner, designer, contractor, subcontractors and suppliers. Delays not caused by parties to the construction project are also identified. The first step in establishing responsibility for delays is to look at the contract and examine contractual responsibilities and duties implied by the law. For the sake of simplicity, it will be assumed that in the case of subcontractor or supplier caused delay, the contractor will be responsible for the subcontractor's or supplier's actions. In the same manner, in the case of delays due to design defects, the owner will be responsible for the designer's actions.

Table 3.1, Table 3.2 and Table 3.3 contain lists of potential causes for construction project delays that were compiled after an extensive literature review (Yates 1993; Elnagar and Yates, 1997; Russell and Fayek, 1994; Bramble and Callahan, 1987; Rubin 1999; Pickavance 2000; Carnell 2000). The lists are incorporated into the as-built database, so that it is possible to select a cause of delay from these lists. The fuzzy logic model is intended to be flexible by allowing the user to edit and augment the causes of delays to suit specific contract clauses.

Table 3.1 Owner's Responsibility For Delays

Delays Caused by the Owner:

- Design modification (changes/additions)
- Quality inspections
- Excessive quality demanded
- More work than planned
- Extra work requested
- Poor scope definition
- Owner interference or stop work orders
- Change orders / requests
- Rework due to change order
- Site not prepared/available
- Change in / unexpected site conditions
- Decision required
- Awaiting approvals
- Delay/change in award of contract
- Conflicting information
- Owner contract administration obligations
- Owner's financial obligations
- Failure to coordinate separate contractors

Delays Caused by the Designer

- Incomplete / insufficient / defective drawings
- Slow correction of design errors
- Poor design coordination
- Late shop drawing review
- Awaiting inspections / tests

Table 3.2 Contractor's Responsibility For Delays

Delays Caused by the Contractor:

- Poor labour supervision
- Poor labour productivity
- Understaffing / Undermanning
- Overstaffing / Overmanning
- Overcrowded work area / Congestion
- Interference of other trades (trade stacking)
- Poor trade coordination
- Workspace not cleaned
- Poor workmanship
- Low skill level
- Excessive turnover
- Low motivation/morale
- Inadequate instructions
- Unsafe practices / accidents
- Fatigue (long shifts / overtime)
- Tool availability
- Insufficient materials
- Inefficient materials handling
- Construction methods
- Layout error
- Rework due to construction or workmanship defects
- Insufficient equipment
- Tools / Equipment breakdowns
- Lack of testing equipment
- Insufficient storage space
- Inadequate external / internal access
- Inaccurate estimates / estimating error
- Failure to evaluate site conditions and design
- Schedule too optimistic
- Inadequate plans
- Work on non-critical tasks
- Poor subcontractor management
- Late engineering
- Contractor's financial obligations

Delays Caused by the Supplier:

- Late equipment delivery
- Damaged deliveries
- Late material delivery
- Poor Material quality
- Rework due to defective material

Delays Caused by the Subcontractor:

- Delay in Subcontractor's work
- Bankruptcy of subcontractors
- Rework due to subcontractor

Table 3.3 Delays not Caused by Parties to the Design and Construction Process

– Weather delay (temperature)	– Environmental issues
– Weather delay (wind)	– Awaiting connection
– Weather delay (precipitation)	– Awaiting inspections/tests
– Weather delay (freeze thaw cycles)	– Interferences of existing utilities
– Craft labor shortage	– Unanticipated utilities
– Labor strike and disputes	– Work damaged by others
– Worker's compensation board shutdown	– Theft/Vandalism
	– Noise level too high
– Awaiting permit approvals	– Natural disaster and acts of God
– Regulatory changes	

3.4.2 Delay Types

A project consists of any number of activities, many of which may be constructed at different times than originally planned. The date of the activity's completion may be slipped due to a delayed start or extended activity duration. The causes that originate a delay in the activity's start may be completely independent to those that generate an extended duration in the activity. If an activity's completion date is delayed, this may generate delays in succeeding activities. The cumulative effect of these delays may cause a delay in the project completion time (Jinsheng and Arditi, 2001).

In this fuzzy logic model, delays are classified according to their occurrence within the activity. An activity's completion time may be delayed due to the following types of delays:

- Type 1: A delay in the start time of the activity caused by delays in the completion of immediately preceding activities.

- Type 2: A delay in the start time of the activity generated by factors related exclusively to the activity itself.
- Type 3: A delay that occurs during the execution of the activity due to factors related to the activity itself, and causes an extended activity duration.

3.4.3 Delay Categories

The second component of the fuzzy logic model is delay categorization. The data contained in the as-built database related to delaying events, is used to categorize the occurrence of each delay according to responsibility. In order to classify delays, a cause/ effect matrix is used as an analytical tool for demonstrating graphically a hierarchical analysis of the multiple cause/effect relationships between the causes of a delay and the category to which the delay belongs: excusable noncompensable, excusable compensable, or nonexcusable. (Pickavance, 2000). The terms used to describe the category of delays are explained in Section 2.3. Figure 3.3 illustrates how a cause/effect matrix is employed in order to relate causes of delays with their corresponding delay category.

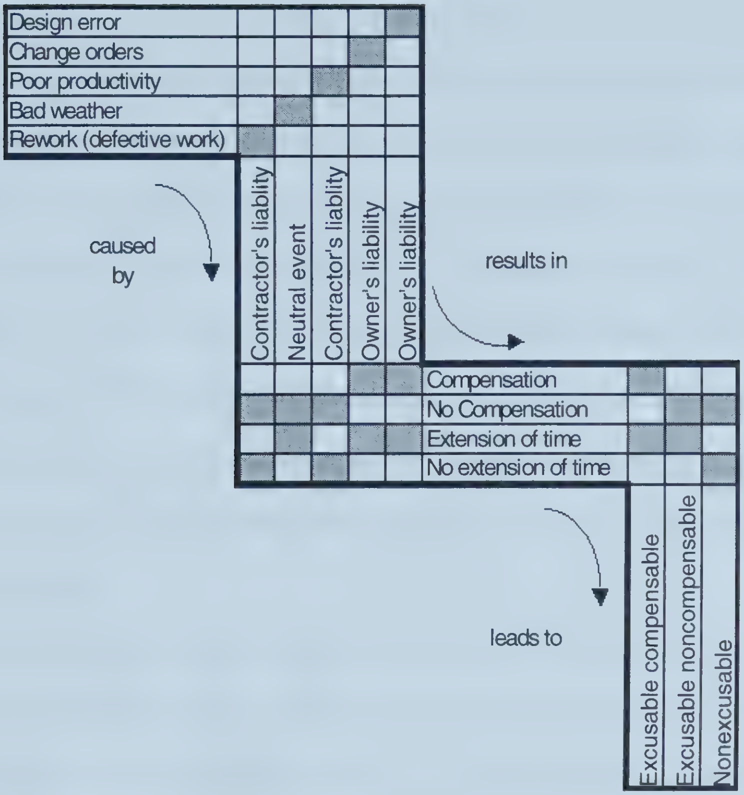


Figure 3.3 Example Cause/effect Matrix to Categorize Delays

3.5 Estimating Delay Impacts

The third component of the fuzzy logic model is the estimation of delay impacts. During the execution of a project, whenever it becomes evident that the progress of the works is being affected by a delaying event, usually project managers produce a written notice of the occurrence of the delay. The notice should contain the cause or causes of delay, the date it took place, its anticipated effects, and the extent of the expected delay. Even though the project manager may have identified the existence of a problem, it will

rarely be possible to assess or determine accurately its full extent, its probable consequences, and whether or not it is likely to delay the project completion date.

The purpose of this portion of the fuzzy logic model is to develop a delay impact estimation procedure for determining the anticipated impact of delaying events on activity durations and the associated time lost due to the amount of disruption in the original activity duration. In order to fully evaluate the overall delaying impact on the schedule, a process for evaluating the impact of a delaying event on an activity is developed. The proposed method provides an opportunity for determining delaying impacts to the schedule that provide a basis for forecasting future activity durations. This method is described in this section.

Linguistic information concerning the impact of delaying events can be evaluated with fuzzy sets. Fuzzy sets will be utilized as a tool for quantifying linguistic variables related to the time impact of delaying events to construction activities. The framework for quantifying linguistic variables is based on the methodology developed by Ayyub and Haldar (1984) and Smith and Hancher (1989). The first step in order to estimate delay impact duration is to determine the set of delay-sensitive attributes, which are described in the next section.

3.5.1 Delay-Sensitive Attributes

Every activity in a project has several characteristics that determine its sensitivity to different causes of delays. Each type of activity will react in a different manner to a specific cause of delay. It is necessary to identify attributes associated with each type of activity, that may determine the particular impact of a delay on the activity. Each activity in the schedule is evaluated separately, considering independently each delay associated

with specific delay-sensitive attributes. A list of activity interpretation attributes was developed by Russell and Fayek (1994), as shown in Table 3.4. These attributes are used to describe activities. The relative sensitivity of an activity to various project conditions, makes it possible to distinguish it from another activity. (Russell and Fayek, 1994). In this research the list of attributes is used to indicate the sensitivity of an activity to a specific delaying impact.

Table 3.4 Delay-Sensitive Attributes. (Russell and Fayek, 1994)

- Sensitivity to duration
- Sensitivity to precipitation
- Sensitivity to temperature
- Sensitivity to humidity
- Sensitivity to wind
- Sensitivity to ground conditions
- Sensitivity to storage on site
- Sensitivity to site congestion
- Sensitivity to internal access
- Sensitivity to external access
- Sensitivity to location of the activity
- How labor intensive
- How material intensive
- How equipment intensive
- Use of innovative methods
- Subject to/requires design changes / additions
- Subject to/requires inspection
- Subject to/requires contract provision
- Subject to/requires controlled environment
- Subject to/requires low tolerance
- Design complexity
- Susceptibility to learning curve effects

The set of delay-sensitive attributes is divided into linguistic states for analysis using fuzzy logic. For each activity suffering a delay, it is necessary to identify the delay-sensitive attributes of the activity and their corresponding linguistic states. In order to do

this, the user will make use of the information stored in the as-built database. In Section 3 of the database, "Information on Delays", a description of the situation that led to the delay as well as the causes of the delay, are input by the user. Based on this information, the user identifies the delay-sensitive attribute that relates to that particular delay and its corresponding linguistic states. The user's assessments with respect to the choice of delay-sensitive attributes as well as its linguistic states, is completely subjective, and depends on the characteristics of the project and the user's judgment of the problem.

The following situation is an example of what the user would do to identify delay-sensitive attributes. A weather delay caused by precipitation is affecting an excavation activity. The delay-sensitive attributes of this activity that will determine the specific effect of the delay on the activity may be as follows:

- Sensitivity to duration of the activity
- Sensitivity to stability
- Sensitivity to ground conditions

The sensitivity to the duration of the activity needs to be considered due to the time exposure. For instance, if an activity has a four-day duration and loses two days due to precipitation delays, the delay impact is large. On the contrary, if an activity has a twenty-day duration and loses two days due to precipitation delays, the delay impact is small because it has a greater potential to make up for lost time during its remaining duration. Based on the above, the linguistic states to be considered for the sensitivity to duration will be as follows: Long duration, Medium duration and Short duration.

The sensitivity to stability indicates the extent to which the excavation activity can be affected by a precipitation delay, depending on the slope angle of the excavation walls. If the slope of the excavation has a height / depth ratio of 1 horizontal to 4 vertical (1H:4V) or greater, then the delay impact is large due to the likelihood of collapsing due to precipitation. On the contrary if the slope of the excavation has a height / depth ratio of 4 horizontal to 1 vertical (4H:1V) or smaller, the delay impact is small due to the reduced likelihood of collapsing due to precipitation. Based on the above, the linguistic states to be considered for the sensitivity to stability of the activity will be as follows: Good stability, Average stability, and Poor stability.

The sensitivity to ground conditions indicates the extent to which the excavation activity can be affected by a precipitation delay, depending on the type of soil. If the soil type on site is clay, the additional humidity is absorbed by the soil increasing the complexity of the excavation process, and therefore the delay impact is large. On the contrary if the soil type is a course gravel soil, the additional humidity is drained by the soil without affecting the excavation process, and therefore the delay impact is small. Based on the above, the linguistic states to be considered for the sensitivity to ground conditions of the activity will be as follows: Good ground conditions, Average ground conditions, and Poor ground conditions.

3.5.2 Procedure for Estimating Delay Impacts

The procedure employed in the fuzzy logic model to estimate delay durations is based on the methodology proposed by Ayyub and Haldar (1984), Yao (1980), and Smith and Hancher (1989). The reader may refer to Appendix A, were an example project is

presented in order to illustrate the method. The procedure to estimate delay impacts is described as follows:

- Step 1: The user identifies the delay-sensitive attributes of the activity suffering a delay, and their corresponding linguistic states. (As described in Section 3.5.1.)

- Step 2: The user estimates the relationship between the state of each attribute and its frequency of occurrence in linguistic terms. For each attribute state, it is necessary to determine the frequency of occurrence with which the delay under consideration will likely affect the activity. The user establishes his or her linguistic perception with respect to the frequency of occurrence, by assessing the potential or likelihood of occurrence of the delay, based on intuition, experience and judgment; and the analysis of the information concerning the delay.

The following linguistic descriptors can be employed by the user to describe the linguistic terms used to assess the frequency of occurrence: *Very Small, Quite Small, Small, Medium, Large, Quite Large,* and *Very Large.*

- Step 3: The user estimates the relationship between the frequency of occurrence of the state of each attribute and its adverse consequences in linguistic terms. For each frequency of occurrence of the state of each attribute, it is necessary to determine the adverse consequences that the occurrence of the delay will produce. The adverse consequences are assessed subjectively based on his or her perception of the magnitude or gravity of the effect that the delay will originate if it should occur.

The following linguistic descriptors can be employed by the user to describe the linguistic terms used to assess the adverse consequences: *Very Small, Quite Small, Small, Medium, Large, Quite Large,* and *Very Large.*

In theory, the number of all possible relationships between the frequency of occurrence of a specific state and its adverse consequences is large. The components of all possible relations can be described in the form of a decision tree. Figure 3.4 shows one delay sensitive-attribute that has three linguistic states. If the frequency of occurrence and adverse consequences can be described using the following three linguist descriptors: *Large, Medium* and *Small*, then there would be twenty-seven (3^3) possible relationships.

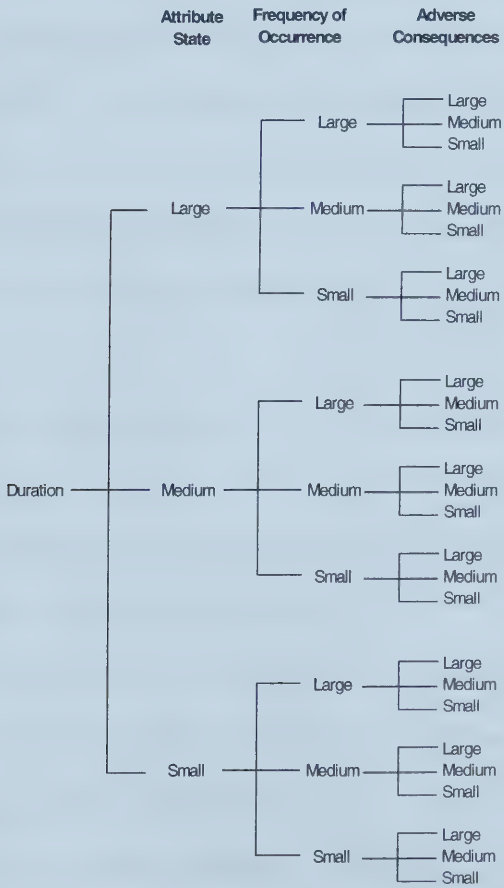


Figure 3.4 Possible relationships between frequency of occurrence and adverse consequences

However, the number of possible relationships can be reduced based on practical consideration and the intuition of the user. The appropriate choice of relation also results from analyzing the situation and causes that led to the delay, as well as the characteristics of the activity under consideration. This analysis will reveal the most likely relation between the frequency of occurrence of a specific state and its adverse consequences. For instance, the following statement may reflect the thought process of the user: "The duration of this activity is medium compared with other activities in the project. There seems some chance, neither large nor small, that the problematic situations that have recently occurred in this activity will continue and thus, could extend the duration of this activity. If the duration of this activity is extended, this will have a direct negative effect on the project completion time". This statement could be interpreted as follows: An activity of medium duration may be affected by a delay that has a medium frequency of occurrence. The delay will have large consequences if it should occur.

Returning to the example presented in the previous section, the user may produce the following assessments with respect to the three delay-sensitive attributes, for the most likely situation in which the excavation activity is affected by a precipitation delay that has a likely medium frequency of occurrence:

- The activity has a Medium duration and it may be affected by a precipitation delay that has a likely Medium frequency of occurrence. The delay will have Large consequences if it should occur.
- The activity has Average sensitivity to stability and it may be affected by a precipitation delay that has a likely Medium frequency of occurrence. The delay will have Medium consequences if it should occur.

- The activity has Good ground conditions and it may be affected by a precipitation delay that has a likely Medium frequency of occurrence. The delay will have Small consequences if it should occur.

Since the frequency of occurrence and adverse consequences of the delay are beyond the control of the user, the outcome of the delay can not be known with absolute certainty. The nature of this situation is fuzzy and the outcome of the delay could deviate from the most likely situation. Different logical outcomes should also be considered to represent the extent of the potential damage if a delay should occur. The following are the user's subjective assessments to account for other possible outcomes with respect to the three delay-sensitive attributes, for a possible situation in which the excavation activity is affected by a precipitation delay that has a likely large frequency of occurrence:

- If the activity had a Long duration, and if it would be affected by a precipitation delay that had a likely Large frequency of occurrence; then the delay would have Large consequences if it should occur.
- If the activity had Low sensitivity to stability, and it if would be affected by a precipitation delay that had a likely Large frequency of occurrence; then the delay would have Medium consequences if it should occur.
- If the activity had Poor ground conditions, and if it would be affected by a precipitation delay that had a likely Large frequency of occurrence; then the delay would have very Large consequences if it should occur.

Table 3.5 contains all subjective assessments produced by the user in order to portray the complete picture of the occurrence of a precipitation delay that affects the activity excavation.

Table 3.5 Delay-sensitive attributes for activity Excavation

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Large Medium Small	Large Large Medium
Sensitivity to Stabilty	High Average Low	Large Medium Large	Very Large Medium Medium
Sensitivity to Ground Conditions	Good Average Poor	Medium Medium Large	Small Medium Very Large

- Step 4: The user translates the linguistic terms into fuzzy sets by assigning membership values to each linguistic term describing the frequency of occurrence and adverse consequences. Equations (3-1) to (3-7) are used in this section to translate linguistic variables into fuzzy sets, although the membership values depend on the project and reflect the user's assessment of the problem. These membership values are presented for illustration purposes only, and are those utilized by Ayyub and Haldar (1984) to demonstrate their proposed methodology. Figure 3.5 is a graphical representation of the membership functions. The following notation is used throughout this thesis to denote membership functions. The fuzzy set "Large" can be defined as:

$$\text{Large} = [x_1 = 0.8 \mid \mu_{\text{Large}}(x_1) = 0.5,\ x_2 = 0.9 \mid \mu_{\text{Large}}(x_2) = 0.9,\ x_3 = 1.0 \mid \mu_{\text{Large}}(x_3) = 1.0]$$

In short, the fuzzy set “Large” can be expressed as:

Large = (0.8|0.5, 0.9|0.9, 1.0|1.0) (3-1)

Small = (0.0|1.0, 0.1|0.9, 0.2|0.5) (3-2)

Medium = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2) (3-3)

Very large = $(\text{Large})^2$ = (0.8|0.25, 0.9|0.81, 1.0|1.0) (3-4)

Quite large = $(\text{Large})^{1.25}$ = (0.8|0.42, 0.9|0.88, 1.0|1.0) (3-5)

Very small = $(\text{Small})^2$ = (0.0|1.0, 0.1|0.81, 0.2|0.25) (3-6)

Quite small = $(\text{Small})^{1.25}$ = (0.0|1.0, 0.1|0.88, 0.2|0.42) (3-7)

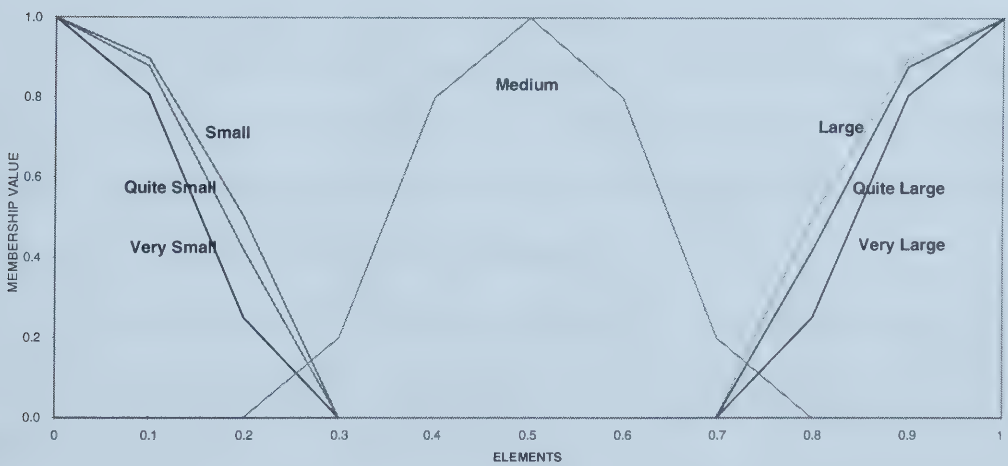


Figure 3.5 Membership functions for linguistic variables representing frequency of occurrence and adverse consequences

Table 3.6 shows an example of how the user translated the linguistic variables into fuzzy sets by assigning the membership values given in equations (3-1) and (3-3).

Table 3.6 Membership values for occurrence and consequences related to attribute Medium Duration

Duration

State:	Medium
Frequency of occurrence:	Medium
Adverse Consequences:	Large

Elements	Frequency of Occurrence	Adverse Consequences
0	0.00	0.00
0.1	0.00	0.00
0.2	0.00	0.00
0.3	0.20	0.00
0.4	0.80	0.00
0.5	1.00	0.00
0.6	0.80	0.00
0.7	0.20	0.00
0.8	0.00	0.50
0.9	0.00	0.90
1	0.00	1.00
Linguistic Variable	**Medium**	**Large**

- Step 5: The fuzzy logic model combines the frequency of occurrence and adverse consequences for each attribute state. This is done by calculating fuzzy relation matrices between the fuzzy set *F*, representing the frequency of occurrence, and the fuzzy set *C*, representing the adverse consequences.

The fuzzy relation *R*, or Cartesian-product, *F* x *C*, between the fuzzy sets *F* (subset of a universe *X*) and *C* (subset of a universe *Y*) is computed as the minimum value of the membership values $\mu_F(x_i)$ and $\mu_C(y_j)$ as follows:

$$\mu_R(x_i, y_j) = \mu_{FxC}(x_i, y_j) = \min \mu_F(x_i), \mu_C(y_j) \tag{3-8}$$

Where $\mu_R(x_i, y_j)$ = Membership value of element (x_i, y_j) in fuzzy relation *R*

$\mu_{FxC}(x_i, y_j)$ = Membership value of element (x_i, y_j) in Cartesian-Product *F x C*

$\mu_F(x_i)$ = Membership value of element x_i in fuzzy set *F*

$\mu_C(y_j)$ = Membership value of element y_j in fuzzy set *C*

x_i = Element of universe X

y_j = Element of universe Y

The fuzzy relation *R,* has the following membership function expressed in matrix form as:

$$R = F\,x\,C = \begin{array}{c|ccccc} & \multicolumn{5}{c}{\textit{Adverse Consequences}} \\ & y_1 & y_2 & \cdots & y_m \\ \hline x_1 & \mu_R(x_1, y_1) & \mu_R(x_1, y_2) & \cdots & \mu_R(x_1, y_m) \\ x_2 & \mu_R(x_2, y_1) & \mu_R(x_2, y_2) & \cdots & \mu_R(x_2, y_m) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_n & \mu_R(x_n, y_1) & \mu_R(x_n, y_2) & \cdots & \mu_R(x_n, y_m) \end{array} \quad \textit{Frequency of Occurrence} \tag{3-9}$$

The fuzzy relation *R*, or cartesian-product, *F x C* may be stated in a conditional form. The example under analysis will be used to illustrate the conditional form of the fuzzy relation *R*. In this case three fuzzy relations may be established: a fuzzy relation R_1, for attribute Medium Duration, given by equation (3-10); a fuzzy relation R_2, for attribute Medium Sensitivity to Precipitation, given by equation (3-11); and a fuzzy relation R_3, for attribute Good Ground Conditions, given by equation (3-12).

The fuzzy relation R_1, for attribute Medium Duration, may be defined as follows: "if the frequency of occurrence of the delay is medium, then the adverse consequences are large".

This expression translated to fuzzy sets is as follows, where the fuzzy set F_1 is defined by equation (3-3), and the fuzzy set C_1 is defined by equation (3-1):

R_1 : If F_1 = Medium frequency of occurrence = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2) then,

C_1= Large adverse consequences = (0.8|0.5, 0.9|0.9, 1.0|1.0)

(3-10)

The fuzzy relation R_2, for attribute Medium Sensitivity to Precipitation, may be defined as follows: "if the frequency of occurrence of the delay is medium, then the adverse consequences are medium".

This expression translated to fuzzy sets is as follows, where the fuzzy set F_2 is defined by equation (3-3), and the fuzzy set C_2 is defined by equation (3-3):

R_2 : If F_2 = Medium frequency of occurrence = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2) then,

C_2 = Medium adverse consequences = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2)

(3-11)

The fuzzy relation R_3, for attribute Good Ground Conditions may be defined as follows: "if the frequency of occurrence of the delay is medium, then the adverse consequences are small".

This expression translated to fuzzy sets is as follows, where the fuzzy set F_3 is defined by equation (3-3), and the fuzzy set C_3 is defined by equation (3-2):

R_3: If F_3 = Medium frequency of occurrence = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2) then,

C_3= Small adverse consequences = (0.0|1.0, 0.1|0.9, 0.2|0.5)

(3-12)

- Step 6: After the fuzzy relation matrices have been developed, the fuzzy logic model determines the total effect of all attribute states on the delay duration. This is done by performing the union of all the relation matrices obtained on Step 5.

The union T, between the fuzzy sets F, and C, is computed in the following manner:

$$T = (F_1 \times C_1)\ U\ (F_2 \times C_2) \ldots\ U\ (F_p \times C_p) \tag{3-13}$$

Where p is the number of fuzzy relations.

The union of two fuzzy relations R_1 and R_2 is defined as:

$$(R_1 \cup R_2)(x_i, y_j) = R_1(x_i, y_j) s R_2(x_i, y_j) \tag{3-14}$$

Where s = s-norm

The following are examples of some s-norms that are frequently used as fuzzy unions (each defined for all $x, y \in [0, 1]$) (Klir and Yuan, 1995):

Standard Union: x s y= max(x,y) (3-15)

Algebraic Sum: x s y= x+y-xy (3-16)

Bounded Sum: x s y= min(1,x+y) (3-17)

$$Drastic \quad Union: \quad xsy = \begin{cases} x \quad when \quad y=0 \\ y \quad when \quad x=0 \\ 1 \quad otherwise \end{cases}$$

(3-18)

In this fuzzy logic model, the standard union given by equation (3-15) will be used to perform the union of fuzzy relations, in order to determine the total effect of all attribute states on the delay duration.

The union of *p* fuzzy relations has the following membership function:

$$\mu_{\overset{p}{\underset{k=1}{\cup}} R_k}(x_i, y_j) = \max_{k=1}^{p}[\mu_{R_k}(x_i, y_j)]$$

(3-19)

Where R_k, for $k = 1, 2, ..., p$, are fuzzy relations.

The union of *p* fuzzy relations is given by equation (3-13) and may be stated in a conditional form: "if F_1 then C_1 or else if F_2 then C_2 ... or else if F_p then C_p". In this way, the total effect of all subjectively predicted attribute states on the delay duration is obtained by merging each fuzzy conditional relation by the union.

Referring to the example under analysis, the union T, may be defined as follows: "if the frequency of occurrence of the delay is medium, then the adverse consequences are large; or else if the frequency of occurrence of the delay is medium, then the adverse consequences are medium; or else if the frequency of occurrence of the delay is medium, then the adverse consequences are small ". This expression is translated to fuzzy sets is as follows:

$$T = R_1 \cup R_2 \cup R_3 = \text{if } F_1 \text{ then } C_1 \text{ or else if } F_2 \text{ then } C_2 \text{ or else if } F_3 \text{ then } C_3 \tag{3-20}$$

Replacing equations (3-10), (3-11) and (3-12) on equation (3-20), the following equation is obtained:

T = If F_1 = Medium frequency of occurrence = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2) then,

C_1 = Large adverse consequences = (0.8|0.5, 0.9|0.9, 1.0|1.0);

or else if F_2 = Medium frequency of occurrence = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2) then,

C_2 = Medium adverse consequences = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2);

or else if F_3 = Medium frequency of occurrence = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2) then,

C_3 = Small adverse consequences = (0.0|1.0, 0.1|0.9, 0.2|0.5)

(3-21)

- Step 7: The user estimates the relationship between the adverse consequences and the delay duration in linguistic terms. The following linguistic descriptors can be employed by the user to describe the relationship between adverse consequences and delay duration: *Very Small, Quite Small, Small, Medium, Quite Large, Large and Very Large*, as defined in Steps 2 and 3.

The user establishes his or her linguistic perception with respect to the delay duration, based on the magnitude or gravity of the adverse consequences on the delay

duration. The following statement may reflect the thought process of the user: "If the consequences are large, then the delay duration is very large. If the consequences are medium, then the delay duration is large. If the consequences are small, then the delay duration is small."

- Step 8: The user translates the linguistic terms into fuzzy sets by assigning membership values to each linguistic term describing the adverse consequences and delay duration. The adverse consequences may be translated by the user using equations (3-1) to (3-7), as explained in Step 4.

In order to translate the linguistic terms describing the delay duration, the user develops membership functions for each fuzzy set representing a linguistic term. Based on his or her subjective judgment, the user establishes membership functions in order to express his or her belief of delay duration. For instance, in order to translate the linguistic term "large delay duration" the user may first produce a subjective assessment of the delay duration values that he or she considers may represent the linguistic term "large". This assessment depends on the causes of the delay, and on the activity and project characteristics. For a particular activity the user may consider a delay duration of 8 days as definitely being large, and a delay duration of 2 days as definitely being small. The user may define "large delay duration" using the following membership function:

$$D_L = \text{Large delay duration} = (2|0.0,\ 3|0.2,\ 5|0.8,\ 8|1.0) \tag{3-22}$$

The user may also express "very large", "medium", "small' and " very small" delay duration as follows:

D_{VL} = Very large delay duration = Large^2 = (2|0.0, 3|0.04, 5|0.64, 8|1.0) (3-23)

D_M = Medium delay duration = (2|0.2, 4|1.0, 5|0.5, 8|0.2) (3-24)

D_S = Small delay duration = (2|1.0, 3|0.8, 6|0.2, 8|0.0) (3-25)

D_{VS} = Very small delay duration = Small^2 (2|1.0, 3|0.64, 6|0.04, 8|0.0) (3-26)

Table 3.7 shows an example of how the user translated the linguistic variables representing the delay duration by assigning the membership values given in equations (3-22), (3-23) and (3-25), and the adverse consequences by assigning the membership values given in equations (3-1), (3-2) and (3-3).

Table 3.7 Fuzzy sets for delay duration and adverse consequences

Delay duration in days:

	(1)	*(2)*	*(3)*
Elements	**Very Large**	**Large**	**Small**
2	0.00	0.00	1.00
3	0.04	0.20	0.80
5	0.64	0.80	0.20
8	1.00	1.00	0.00

Adverse Consequences:

	(1)	*(2)*	*(3)*
Elements	**Large**	**Medium**	**Small**
0	0.00	0.00	1.00
0.1	0.00	0.00	0.90
0.2	0.00	0.00	0.50
0.3	0.00	0.20	0.00
0.4	0.00	0.80	0.00
0.5	0.00	1.00	0.00
0.6	0.00	0.80	0.00
0.7	0.00	0.20	0.00
0.8	0.50	0.00	0.00
0.9	0.90	0.00	0.00
1	1.00	0.00	0.00

- Step 9: The fuzzy logic model combines the adverse consequences and delay duration. This is done by calculating fuzzy relation matrices between the fuzzy set *C*, representing the adverse consequences, and the fuzzy set *D*, representing the delay duration.

The fuzzy relation *Q*, or Cartesian-product, *C x D*, between the fuzzy sets *C* (subset of a universe *Y*) and *D* (subset of a universe *Z*) is computed as the minimum value of the membership values $\mu_C(y_j)$ and $\mu_D(z_k)$, as follows:

$$\mu_Q(y_j, z_k) = \mu_{CxD}(y_j, z_k) = \min \mu_C(y_j), \mu_D(z_k) \tag{3-27}$$

Where $\mu_Q(y_j, z_k)$ = membership value of element (y_j, z_k) in fuzzy relation *Q*

$\mu_{CxD}(y_j, z_k)$ = membership value of element (y_j, z_k) in Cartesian-Product *C x D*

$\mu_C(y_j)$ = Membership value of element y_j in fuzzy set *C*

$\mu_D(z_k)$ = Membership value of element z_k in fuzzy set *D*

y_j = Element of universe *Y*

z_k = Element of universe *Z*

The fuzzy relation has the following membership function expressed in matrix form as:

$$R = C\,x\,D = \begin{array}{c} \\ \textit{Adverse Consequences} \end{array} \begin{array}{c|cccc} & \multicolumn{4}{c}{\textit{Delay Duration}} \\ & z_1 & z_2 & \cdots & z_m \\ \hline y_1 & \mu_R(y_1, z_1) & \mu_R(y_1, z_2) & \cdots & \mu_R(y_1, z_m) \\ y_2 & \mu_R(y_2, z_1) & \mu_R(y_2, z_2) & \cdots & \mu_R(y_2, z_m) \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ y_n & \mu_R(y_n, z_1) & \mu_R(y_n, z_2) & \cdots & \mu_R(y_n, z_m) \end{array} \tag{3-28}$$

The fuzzy relation Q, or Cartesian-product, $C \times D$ may be stated in a conditional form. The example under analysis will be used to illustrate the conditional form of the fuzzy relation Q. In this case three fuzzy relations may be established between the adverse consequences and the delay duration: a fuzzy relation Q_1, given by equation (3-29); a fuzzy relation Q_2, given by equation (3-30); and a fuzzy relation Q_3, given by equation (3-31).

The fuzzy relation Q_1 may be defined as follows: "if the adverse consequences are large, then the delay duration is very large".

This expression translated to fuzzy sets is as follows, where the fuzzy set C_1 is defined by equation (3-1), and the fuzzy set D_1 is defined by equation (3-23):

Q_1: If C_1= Large adverse consequences = (0.8|0.5, 0.9|0.9, 1.0|1.0) then,

D_1= Very large delay duration = (2|0.0, 3|0.04, 5|0.64, 8|1.0)

(3-29)

The fuzzy relation Q_2 may be defined as follows: "if the adverse consequences are medium, then the delay duration is large".

This expression translated to fuzzy sets is as follows, where the fuzzy set C_2 is defined by equation (3-3), and the fuzzy set D_2 is defined by equation (3-22):

Q_2: If C_2= Medium adverse consequences = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2) then,

D_2= Large delay duration = (2|0.0, 3|0.2, 5|0.8, 8|1.0)

(3-30)

The fuzzy relation Q_3 may be defined as follows: "if the adverse consequences are small, then the delay duration is small".

This expression translated to fuzzy sets is as follows, where the fuzzy set C_3 is defined by equation (3-2), and the fuzzy set D_3 is defined by equation (3-25):

Q_3 : If C_3 = Small adverse consequences = (0.0|1.0, 0.1|0.9, 0.2|0.5) then,

D_3= *Small* delay duration = (2|1.0, 3|0.8, 6|0.2, 8|0.0)

(3-31)

• Step 10: After the fuzzy relation matrices have been developed, the fuzzy logic model performs the union matrix of all the relation matrices obtained in Step 9. The union *V*, between the fuzzy sets *C*, and *D*, is computed in the following manner:

$$V = (C_1 \times D_1) \cup (C_2 \times D_2) \ldots \cup (C_p \times D_p)$$

(3-32)

Where *p* is the number of fuzzy relations.

The union of *p* fuzzy relations has the following membership function:

$$\mu_{\bigcup_{k=1}^{p} Q_k}(y_i, z_j) = \max_{k=1}^{p}[\mu_{Q_k}(y_i, z_j)]$$

(3-33)

Where Q_k, for *k = 1, 2, …., p*, are the fuzzy relations.

The union of *p* fuzzy relations is given by equation (3-32) and may be stated in a conditional form: "if C_1 then D_1 or else if C_2 then D_2 … or else if C_p then D_p". In this way,

the total effect of all adverse consequences on the delay duration is obtained by merging each fuzzy conditional relation by the union.

Referring to the example under analysis, the union *V*, may be defined as follows: "if the adverse consequences are large, then the delay duration is very large; or else if the adverse consequences are medium, then the delay duration is large; or else if the adverse consequences are small, then the delay duration is small". This expression is translated to fuzzy sets is as follows:

$$V = Q_1 \cup Q_2 \cup Q_3 = \text{if } C_1 \text{ then } D_1 \text{ or else if } C_2 \text{ then } D_2 \text{ or else if } C_3 \text{ then } D_3 \tag{3-34}$$

Replacing equations (3-29), (3-30) and (3-31) on equation (3-34), the following equation is obtained:

V = If C_1 = Large adverse consequences = (0.8|0.5, 0.9|0.9, 1.0|1.0) then,

D_1= Very large delay duration = (2|0.0, 3|0.04, 5|0.64, 8|1.0);

or else if C_2 = Medium adverse consequences = (0.3|0.2, 0.4|0.8, 0.5|1.0, 0.6|0.8, 0.7|0.2) then.

D_2= Large delay duration = (2|0.0, 3|0.2, 5|0.8, 8|1.0);

or else if C_3 = Small adverse consequences = (0.0|1.0, 0.1|0.9, 0.2|0.5) then,

D_3= *Small* delay duration = (2|1.0, 3|0.8, 6|0.2, 8|0.0)

(3-35)

- Step 11: In order to estimate the delay duration, the fuzzy logic model performs a fuzzy composition matrix by taking the composition of the union matrices *T* and *V*, which are given in equations (3-13) and (3-32), respectively. Matrix *T* is a fuzzy relation from *X* to *Y*, and matrix *V* is a fuzzy relation from *Y* to *Z*.

The composition of the fuzzy relations *T(X,Y)* and *V(Y,Z)*, which is denoted by *T(X,Y)* o *V(Y,Z)*, produces a relation *ToV(X,Z)* defined by equations (3-36) and (3-37) (Klir and Yuan, 1995):

$$T \circ V(x_i, z_k) = \sup_{y_j}[T(x_i, y_j) t V(y_j, z_k)] \tag{3-36}$$

Where *sup* = Supremum

t = t-norm

$$T \bullet V(x_i, z_k) = \inf_{y_j}[T(x_i, y_j) s V(y_j, z_k)] \tag{3-37}$$

Where *inf* = Infimum

s = s-norm

Equation (3-36) generalizes the standard max-min composition, where *sup* refers to *max*, and *t* refers to *min*. Equation (3-37) generalizes the standard min-max composition, where *inf* refers to *min*, and *s* refers to *max*. The *max-min* composition method is used to perform the composition of *T* and *V*, which is a fuzzy relation that is described by the following membership function:

$$\mu_{ToV}(x_i, z_k) = \max_{y_j}\{\min[\mu_T(x_i, y_j), \mu_V(y_j, z_k)]\} \tag{3-38}$$

Where $\mu_{ToV}(x_i, z_k)$ = Membership value of element (x_i, z_k) in the composition matrix between *T* and *V*.

$\mu_T(x_i, y_j)$ = Membership value of element (x_i, y_j) in the fuzzy relation *T*

$\mu_V(y_j, z_k)$ = Membership value of element (y_j, z_k) in the fuzzy relation *V*

Equation (3-38) gives the membership values for different elements of the delay duration and frequencies of occurrence considering the total effect of the delay-sensitive attributes on the delay duration. The composition matrix has the following membership function expressed in matrix form as:

$$T \circ V = \begin{array}{c|cccc} & \multicolumn{4}{c}{\textit{Delay Duration}} \\ & z_1 & z_2 & \cdots & z_m \\ \hline x_1 & \mu_{ToV}(x_1, z_1) & \mu_{ToV}(x_1, z_2) & \cdots & \mu_{ToV}(x_1, z_m) \\ x_2 & \mu_{ToV}(x_2, z_1) & \mu_{ToV}(x_2, z_2) & \cdots & \mu_{ToV}(x_2, z_m) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_n & \mu_{ToV}(x_n, z_1) & \mu_{ToV}(x_n, z_2) & \cdots & \mu_{ToV}(x_n, z_m) \end{array} \quad \textit{(Frequency of Occurrence)} \tag{3-39}$$

Matrix *T(X,Y)* represents the relationship between the frequency of occurrence set *F*, and the adverse consequences set *C*. Matrix *V(Y,Z)* represents the relationship between the adverse consequences set *C* and the delay duration set *D*. The composition matrix *ToV(X,Z)* relates the two sets through their respective relationship to a third common set. The composition matrix *ToV(X,Z)* evaluates the relation between the fuzzy set *F*, and the fuzzy set *D*, using the fuzzy relations of *F* and *D* to their common fuzzy set *C*. The composition matrix determines a subjective estimation of the delay duration by establishing the relation between a frequency of occurrence and its corresponding subset of delay duration.

Ayyub and Haldar (1984) proposed to choose from equation (3-39) a fuzzy subset *S* that represents the delay duration. A row (subset *S*) is selected from equation (3-39) which maximizes the product of the row summation and its corresponding frequency of

occurrence. The membership function of the fuzzy subset *S* can be represented as follows:

$$S = [z_1 \mid \mu_S(z_1), z_2 \mid \mu_S(z_2), \ldots, z_m \mid \mu_S(z_m)] \tag{3-40}$$

Where z_k = Element of the delay duration

$\mu_S(z_k)$ = Membership value of element z_k on fuzzy subset *S*

m = Number of delay duration elements

The example under analysis will be used to exemplify the procedure to determine fuzzy subset *S*. Figure 3.6 represents the composition matrix of *T* and *V*, calculated using equation (3-39).

Frequency of Occurrence	*Delay Duration* 3	4	5	6	7	Row Summation	Frequency Product
0	1.00	0.64	0.04	0.00	0.00	1.68	0.00
0.1	0.90	0.64	0.04	0.00	0.00	1.58	0.16
0.2	0.50	0.50	0.04	0.00	0.00	1.04	0.21
0.3	0.00	0.10	0.20	0.20	0.20	0.70	0.21
0.4	0.00	0.10	0.30	0.60	0.80	1.80	0.72
0.5	0.00	0.10	0.30	0.60	1.00	2.00	1.00
0.6	0.00	0.10	0.30	0.60	0.80	1.80	1.08
0.7	0.00	0.10	0.20	0.20	0.20	0.70	0.49
0.8	0.00	0.00	0.09	0.25	0.25	0.59	0.47
0.9	0.00	0.00	0.09	0.36	0.81	1.26	1.13
1.0	0.00	0.00	0.09	0.36	1.00	1.45	1.45

Figure 3.6 Composition Matrix: *T o V = max { min [T(F,C) , V(C,D)] }*

As can be seen in Figure 3.6, the row summation of the membership values in the composition matrix was performed. Each row summation value is then multiplied by its corresponding frequency of occurrence. A row (subset *S*) is selected from the composition matrix in Figure 3.6 which attains the maximum value of the product of the row summation and its corresponding frequency of occurrence.

The fuzzy subset *S* selected in Figure 3.6 represents the delay duration and gives the membership values for different elements of the delay duration. As can be seen in Figure 3.6, the delay duration is represented by a fuzzy subset whose membership values extend to infinity beyond the last element of the delay duration, that is beyond 7 days. This fuzzy subset is implying that the delay duration may attain any possible value beyond 7 days, a result that is not realistic. In construction scheduling the definition of the duration of an activity, or the duration of a delay in this case, is commonly represented using an unimodal probability mass function. For this reason the fuzzy subset *S* is not used in this fuzzy logic model to represent the delay duration, because it will produce unrealistic results during the process of revising activity durations, which is done on the fourth component of the fuzzy logic model. The fuzzy subset *S* is used to determine probability density function (PDF) of the delay duration and subsequently this PDF is transformed into a triangular membership function by the fifth component of the fuzzy logic model.

This transformation needs to be performed because the component that recalculates and updates the schedule uses a technique that employs triangular membership functions to model the uncertainty related to the estimation of activity durations. This representation of the delay duration is realistic because it possesses only

one possible value, and the spread of the triangular distribution indicates the degree of fuzziness or uncertainty related to the estimation of the delay duration.

- Step 12: The fuzzy logic model selects from equation (3-39), a fuzzy subset for the delay duration represented by equation (3-40). Next, the fuzzy logic model calculates the probability of occurrence for each element z_K of the delay duration as follows:

$$P(D = z_k) = \frac{\mu_S(z_k)}{\sum_{k=1}^{m} \mu_S(z_k)} \tag{3-41}$$

Where $P(D_D = z_k)$= Probability of occurrence of the delay duration to be element z_K

D_D = Delay duration

The fuzzy logic model uses equations (3-42) and (3-43) to estimate the values for mean, μ_D, and standard deviation, σ_D, of the delay duration. These parameters determine the probability density function (PDF) of the delay duration:

$$\mu_D = \sum_{k=1}^{m} (z_k) \times P(D_D = z_k) \tag{3-42}$$

$$\sigma_D = \sqrt{[\sum_{k=1}^{m} (z_k)^2 \times P(D = z_k)] - \mu_D^2} \tag{3-43}$$

With respect to the choice of the fuzzy subset S, Yao (1980) proposed that the membership value of the fuzzy subset S of delay duration should be equal to the largest membership value in the corresponding column for that delay duration. Ayyub and

Haldar (1984) considered that if Yao's method was used for this case, the frequency of occurrence of the total effects of the attributes would not be considered. For instance, the following fuzzy subset could be obtained using Yao's method:

$$S = (3|1.0, 4|0.64, 5|0.3, 6|0.6, 7|1.0) \tag{3-44}$$

The duration of this delay is expected to be between 3 and 7 days. According to equations (3-42) and (3-43), the PDF of the delay duration is a unimodal function, where the modal value represents the most probable delay duration. However, equation (3-44) has two most probable values ($z_1 = 3$ and $z_5 = 7$). This indicates that this is a bimodal function. Ayyub and Haldar (1984) considered that a bimodal function is not realistic since it is common to represent the delay duration by a unimodal function.

As can be seen in Figure 3.6 the fuzzy subset S selected using the method by Ayyub and Haldar, represents a unimodal PDF with the modal value (the most probable delay duration) of 7 days. Consequently, the method proposed by Ayyub and Haldar is more realistic than the method proposed by Yao. (Ayyub and Haldar, 1984).

Determining the values for mean, μ_D, and standard deviation, σ_D, of the delay duration, concludes the calculations corresponding to this portion of the fuzzy logic model. These parameters determine the probability density function (PDF) of the delay duration, which will be used as the input of the next component of the fuzzy logic model. The next component transforms the PDF's representing delay durations into triangular fuzzy numbers.

3.6 Possibility and Probability Transformations

The purpose of this section is to present the fourth component of the fuzzy logic model and to present a mapping between probability density functions (PDF) and membership functions. This is done in order to transform the PDF that represents the delay duration, obtained as the output of the third component of the fuzzy logic model, into a triangular membership function representing the delay duration. The resulting membership function is used as the input of the fifth component of the fuzzy logic model, which revises activity durations.

This section examines some relationships between probability theory and possibility theory. Probability and fuzzy sets are viewed as two different approaches with the common purpose of dealing with uncertainty. For this reason, fuzzy sets and probability can be considered as complementary concepts, as opposed to antagonistic ideas (Pedrycz and Gomide, 1998).

3.6.1 Estimation of Triangular Membership Functions From Probability Density Functions

The triangular membership function is preferred by many researchers due to its simplicity in representing fuzzy numbers, as Lorterapong and Moselhi (1996), state, "Though fuzzy numbers can take various shapes, linear approximations such as triangular and trapezoidal fuzzy numbers are used frequently." The triangular membership function also possesses some of the same properties described for the π-curve function. A triangular function is sufficient to represent the perception of a fuzzy number such as "about 5", because it indicates that: (1) the membership grade for the number 5 is the maximum, (2) the membership grade for the other numbers reduces as

the number deviates from 5, and (3) the membership function is established over a narrow range of values concentrating around 5 (Juang et al.,1992).

The fuzzy model developed in this study, makes use of the methodology proposed by Ayyub and Haldar (1984) to determine the duration of delays that affect the progress of construction activities. The outputs of this method are estimates of the mean value and standard deviation of the duration of a delaying event. It is possible to generate the PDF of the delay duration using the parameters obtained by this technique.

Figure 3.7 represents the activity duration PDF that corresponds to the example utilized by Ayyub and Haldar (1984) to illustrate the application of the method. The parameters of the activity duration are the mean μ_D = 18.7 days and standard deviation σ_D = 1.522 days.

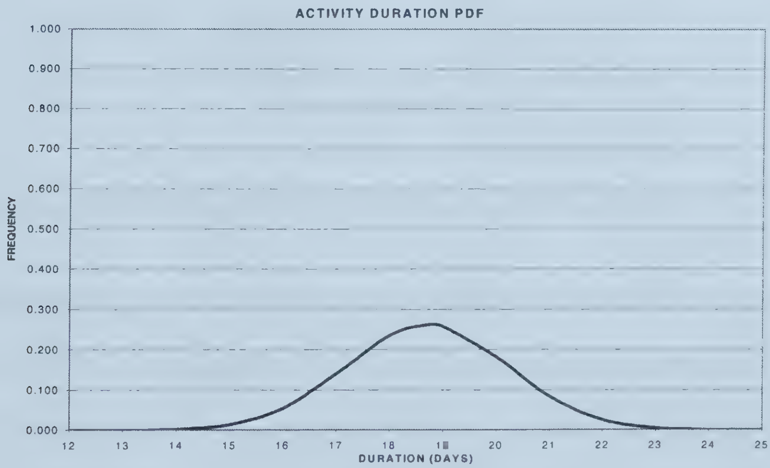


Figure 3.7 Activity duration PDF

The values of the PDF curve are then transformed according to Dubois and Prade (1986) to obtain the membership function curve. Figure 3.8 illustrates the transformation performed.

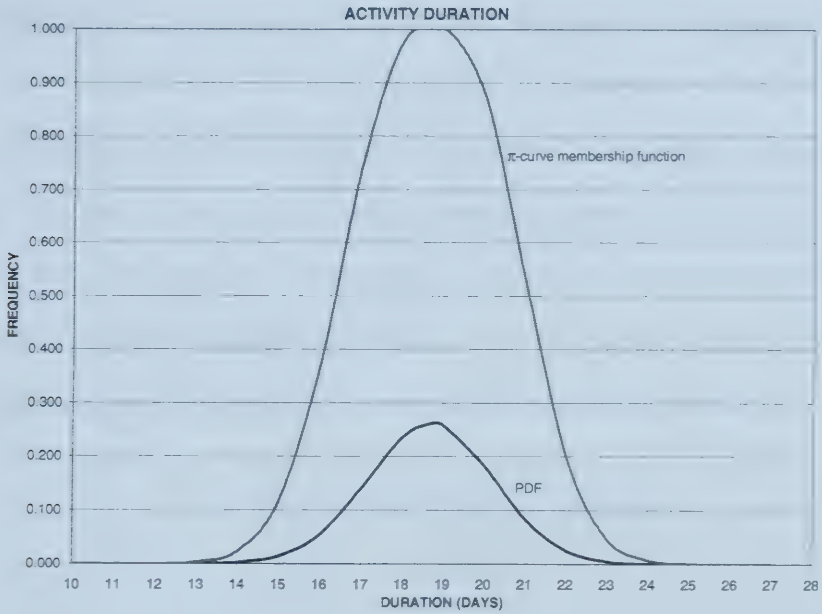


Figure 3.8 Activity PDF duration and π-curve membership function

Referring to Figure 3.8, the membership function obtained is bell shaped. In order to define the π-curve, it is necessary to determine the range parameters *a* and *c* (Refer to Figure 2.2). Parameter *a* corresponds to the mean value, in this case $a = 18.7$. Parameter *c* is determined by calculating the area under the membership function that corresponds to the maximum value of the cumulative function, in this case $c = 4.88$. Since the area under the curve is one half of the range over which the function is defined, the bounds are determined as follows: $a - c = 13.82$ and $a + c = 23.58$. Referring to

Figure 3.8, it can also be seen that the membership functions of the values $a - c / 2$ (16.26) and $a + c / 2$ (21.14), is 0.5.

Since the π-curve is symmetrical and unimodal, it is possible to generate a triangular membership function from this curve. A trapezoidal membership function would be impossible to generate from the π-curve, because it would require two modal values.

A triangular fuzzy number can be represented by the lower bound, the modal value, and the upper bound. The value for these parameters can be taken from those corresponding to the π-curve. Figure 3.9 is a graphical representation of the fuzzy number obtained. As can be seen, the area of the fuzzy number is equal to ½(4.88 x 2) = 4.88, and it is equal to the area under the π-curve membership function.

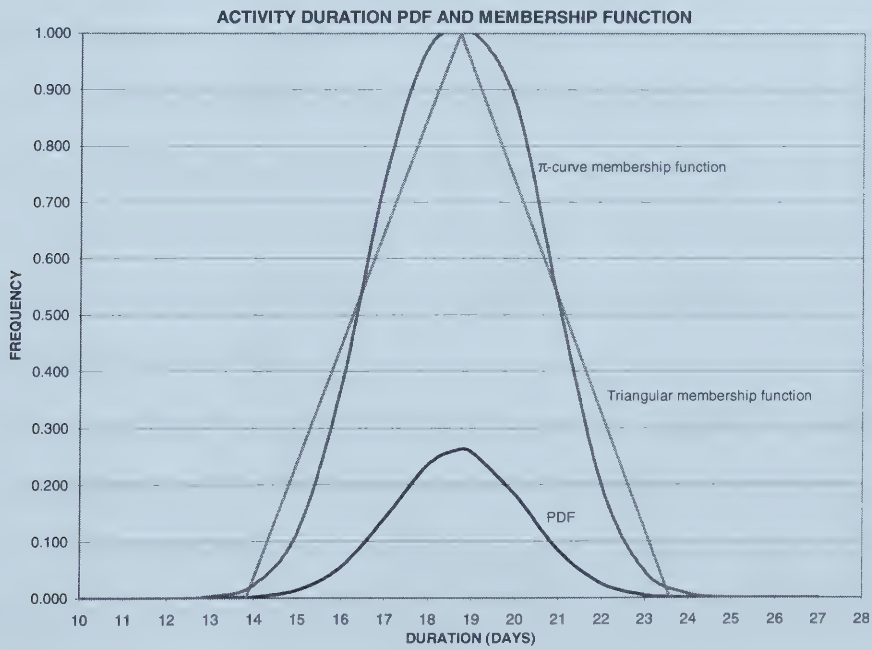


Figure 3.9 Activity duration PDF, π-curve and Triangular membership functions

The reader may refer to Appendix A, were an example project is presented in order to illustrate the procedure to estimate triangular membership functions from probability density functions

3.7 Revised Activity Durations

The fifth component of the model deals with revising activity durations, based on delaying events and progress to date. Whenever a delay occurs, the model revises the activity duration and increases it by the amount of the delay duration. Delays affecting a certain activity are analyzed independently based on their sequence of occurrence. For each delay, the following data are required in order to revise the activity duration: original planned duration of the activity, periods of productive work or normal progress, remaining duration, date of occurrence of the delay, and its resulting delay duration.

Figure 3.10 shows an activity that has an original duration of two weeks. One week of normal progress is performed when a delay occurs on the activity. The progress date selected to perform a snapshot is the beginning of week 3, when the delay occurs. Since the date of the snapshot corresponds to the date of the occurrence of delays, the final delay duration is not known with certainty. When the delay is completed, there is still one week of work to be performed.

Periods of normal progress and periods of remaining duration are known with certainty because together they form the original activity duration. For this reason the durations of these periods are crisp. Periods of delays or nonproductive work are represented by fuzzy numbers and thus are fuzzy. The fuzzy logic model calculates the delay duration, using the methodology explained in Section 3.5. The outputs of this method are estimates of the mean value and standard deviation of the delay duration.

The PDF of the delay duration is generated by the fuzzy logic model using the parameters of the delay duration. The values of the PDF curve are then transformed by the fuzzy logic model into a fuzzy membership function. This triangular fuzzy number corresponds to the output of the process described in Section 3.6.

Since the activity was affected by a delay, the overall activity progress is comprised by sequential portions of productive work represented by crisp numbers; and portions of delays or nonproductive work, represented by fuzzy numbers. Fuzzy addition is employed in order to quantify the different portions of activity duration and to determine the revised actual activity duration obtained after it has been impacted by a delay.

The reader may refer to Appendix A, were an example project is presented in order to illustrate the procedure used to revise activity durations.

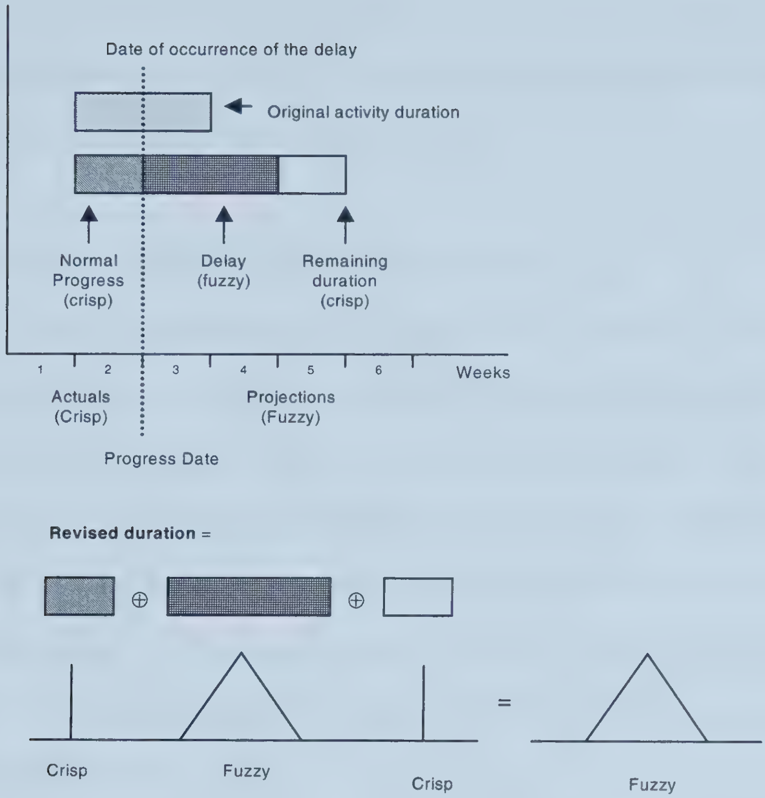


Figure 3.10 Revised Activity Durations

3.8 Forecast Progress at Completion

This section describes the eighth component of the fuzzy logic model that is related with forecasting progress at completion. The overall revised activity duration obtained from the previous step can be represented utilizing fuzzy numbers. This provides the impetus for making use of the fuzzy network scheduling methodology (FNET) proposed by Lorterapong and Moselhi (1996). By employing this method, the schedule can be recalculated in terms of revised activity durations, so that actual fuzzy

early start and finish times can be determined, as well as a revised project completion time, accounting for the impacts of actual delays. The dates and durations of the updated schedule constitute the forecast progress at completion.

3.8.1 Procedure for forecasting progress at completion

The fuzzy logic model utilizes the fuzzy activity durations obtained in Section 3.7, represented as triangular fuzzy numbers, as inputs to the FNET procedure. The outputs produced by the FNET method are fuzzy early and late times of each activity in the schedule obtained from the forward and backward pass calculations. In addition to the scheduling results of fuzzy early and late times for each activity, the fuzzy logic model also calculates the degree of criticality of project activities and an approximate total float for each activity. The following sections explain the FNET methodology proposed by Lorterapong and Moselhi (1996).

3.8.1.1 Forward and Backward Passes

The scheduling calculations for the forward and backward passes are summarized in this section. For further details on the methodology employed, the reader can refer to Lorterapong and Moselhi (1996). Figures 3.11 and 3.12 are not used in the FNET methodology. These figures are included for the purpose of illustrating the fuzzy forward and backward calculations.

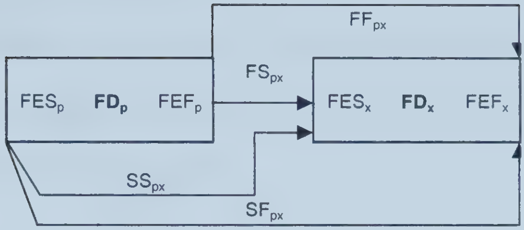


Figure 3.11 Fuzzy Forward Pass

x = Activity under analysis

FES_x = Fuzzy early start of activity x

FEF_x = Fuzzy early finish of activity x

FD_x = Fuzzy duration of activity x

p = Predecessor activity

FES_p = Fuzzy early start of activity p

FEF_p = Fuzzy early finish of activity p

FD_p = Fuzzy duration of activity p

FS_{px} = Finish to Start lag time from p to x

SS_{px} = Start to Start lead time from p to x

FF_{px} = Finish to Finish lag time from p to x

SF_{px} = Start to Finish lead time from p to x

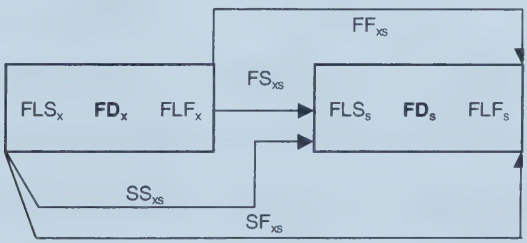


Figure 3.12 Fuzzy Backward Pass

x = Activity under analysis

FLS_x = Fuzzy late start of activity x

FLF_x = Fuzzy late finish of activity x

FD_x = Fuzzy duration of activity x

s = Successor activity

FLS_s = Fuzzy late start of activity s

FLF_s = Fuzzy late finish of activity s

FD_s = Fuzzy duration of activity s

FS_{xs} = Finish to Start lag time from x to s

SS_{xs} = Start to Start lead time from x to s

FF_{xs} = Finish to Finish lag time from x to s

SF_{xs} = Start to Finish lead time from x to s

• Fuzzy forward pass calculations

Lorterapong and Moselhi (1996) utilized traditional forward pass calculations such as those employed in the critical path method (CPM). The following are the fuzzy operations used to compute fuzzy early times:

$$FES_x = \underset{p \in P}{\tilde{\max}}(FEF_P) \tag{3-45}$$

$$FEF_x = FES_x \oplus FD_x \tag{3-46}$$

$$T_{proj} = FEF_e \tag{3-47}$$

Where P = Set of predecessors

T_{proj} = Project duration

e = Last activity in the project

Equations (3-45) through (3-47) where conceived by Lorterapong and Moselhi (1996) to be used solely on projects where the relationship between activities is finish-to-start, with no time lag. Differing from the methodology proposed by Lorterapong and Moselhi (1996), the author proposes the following more general equations to be used when the activities have lead /lag relationships (Refer to Figure 3.11):

$$FES_x = \underset{p \in P}{\tilde{\max}} \begin{Bmatrix} FES_P \oplus SS_{px} \\ or \\ FEF_P \oplus FS_{px} \end{Bmatrix} \tag{3-48}$$

$$FEF_x = \underset{p \in P}{\widetilde{\max}} \begin{Bmatrix} FEF_P \oplus FF_{px} \\ or \\ FES_P \oplus SF_{px} \\ or \\ FES_x \oplus FD_x \end{Bmatrix}$$

(3-49)

Equation (3-45) corresponds to the second case of equation (3-48), where the lag time $FS_{px} = 0$. Equation (3-46) corresponds to the third case of equation (3-49). In the case of interruptible activities, equation (3-46) may be replaced by the following equation:

$$FEF_x = FES_x \oplus FD_x \oplus FI_x$$

(3-50)

Where FI_x = Fuzzy Interruption on activity x.

- Fuzzy backward pass calculations

In FNET, the calculations for the backward pass differ from the traditional backward pass calculations employed in CPM. The reason for this is that Lorterapong and Moselhi (1996) determined that if fuzzy subtraction (equation 2-12) was used in the backward pass calculations, fuzzy late times of project activities have unrealistically large uncertainties. This problem occurs due to two reasons, the first one is that fuzzy addition is not the inverse of fuzzy subtraction; and the second one is that if a fuzzy number results from previous arithmetic operations, its spread increases as the number of operations increases. This fact produces unrealistic accumulations of uncertainty that accumulate while performing the backward pass calculations (Lorterapong and Moselhi, 1996).

To overcome this deficiency, Lorterapong and Moselhi (1996) proposed a new technique to perform backward pass calculations. The starting point of this technique is based on the assumption that "the right spread of fuzzy late times are at least as uncertain as their respective fuzzy early times". The reason for this assumption is the fact that the magnitude of uncertainty related with the finish time of an activity can be assumed to be equal to the addition of the uncertainties of its start time and of its own duration.

The reason why Lorterapong and Moselhi (1996) used the right spread of the fuzzy late times is described as follows: Consider a fuzzy late time of an activity represented by a closed trapezoidal fuzzy number. This late time denotes the latest possible time period by which the activity must be completed. The left portion of Figure 3.13 shows a fuzzy late time given by the quadruples (*a, b, c, d*).

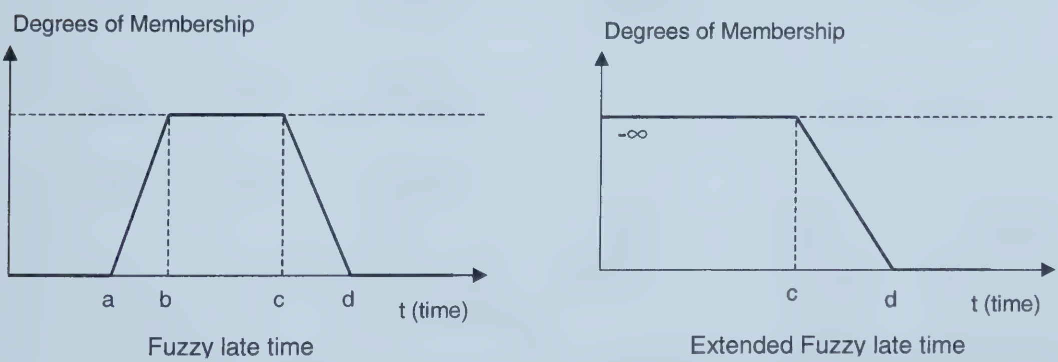


Figure 3.13 Extended Fuzzy Late Time

When the backward pass calculations are performed, all the calculated time elements that have values beyond the upper bound of the trapezoidal fuzzy number in Figure 3.13, are not possible. This means that no values beyond element *d* in the

quadruple (*a, b, c, d*), are possible. If the fuzzy late time is altered by extending its lower boundary (i.e., the left spread) to infinity, all the time elements that occur before its lower bound are possible. This means that all values before element *a* in the quadruple (*a, b, c, d*) are possible. The right portion of Figure 3.13 shows the extended fuzzy late time given by the quadruples ($-\infty$, $-\infty$, *c, d*).

It can be noted that after modifying the fuzzy late time, the degrees of possibility for the time elements located after *d* continue unchanged. As a result of this process, the original fuzzy late finish constraint remains valid, and the fuzzy duration obtained can still be employed in the calculations. The extended fuzzy late time that was created in this process is called the fuzzy upper bound. (Lorterapong and Moselhi, 1996). An example of the fuzzy upper bound is shown in Figure 2.8.

The conversion of a trapezoidal fuzzy number A, given by the quadruple (*a, b, c, d*), to its upper bound A^u; can be obtained by subtracting an interval $(0, \infty)$, expressed in the form of the quadruple (0, 0, ∞, ∞), as follows:

$$A^u = (a,b,c,d) \;\Theta\; (0,0,-\infty,-\infty) = (-\infty,-\infty,c,d) \tag{3-51}$$

The fuzzy backward pass calculations proposed by Lorterapong and Moselhi (1996), for the late times of each activity are explained, as follows:

- Step 1: The process begins by determining the activity's preliminary late finish (*PLF*). The definition of *PLF* is analogous to the late finish time used in CPM. The *PLF* of an activity takes the smallest *FLS* of its successors:

$$PLF_x = \underset{s \in S}{\widetilde{\min}}(FLS_s) \tag{3-52}$$

Where S = set of successors

- Step 2: The PLF_x determined on Step 1 is then converted to the upper bound for the late finish (FLF^u) using equations (3-51) and (3-52).

$$FLF^u = PLF_X \quad \Theta \quad (0,0,-\infty,-\infty) \tag{3-53}$$

- Step 3: Based on the calculated FLF^u and FEF_x, and the assumption stated before relative to the propagation of uncertainty, the fuzzy late finish FLF_x is calculated. In order to do this, the fuzzy quantities FLF^u, given by ($-\infty$, $-\infty$, *e, f*), and FEF_x, given by (*a, b, c, d*), are used as follows:

  - The right spread of the FLF^u given by (*f* - *e*), and that of the FEF_x, given by (*d* - *c*), are compared.

  - The fuzzy number Y is calculated. This number is defined as the largest fuzzy number that satisfies the following condition:

$$FEF_x \oplus Y \subseteq FLF^u \tag{3-54}$$

  - After the comparison, if $(d - c) \geq (f - e)$, then the right spread of FEF_x is more uncertain. In this case, the right spread of FLF_x assumes its value from that of FEF_x. The quadruples of the fuzzy number Y are calculated as the difference between the elements

of the upper bound values of FLF^u and FEF_x. The quadruples of the fuzzy number Y are calculated as: $Y = (f - d, f - d, f - d, f - d)$.

- After the comparison, if $(f - e) > (d - c)$, then the right spread of FLF^u is more uncertain. In this case, the right spread of FLF_x is set equal to that of FLF^u. The left spread and the plateau of the FLF_x are calculated as the difference between the elements of the upper modal values of FLF^u and FEF_x. The quadruples of the fuzzy number Y are calculated as: $Y = (e - c, e - c, e - c, f - d)$

- Step 4: The FLF_x and FLS_x are calculated respectively using:

$$FLF_x = FEF_x \oplus Y \tag{3-55}$$

$$FLS_x \oplus FD_x = FLF_x \tag{3-56}$$

Differing from the methodology proposed by Lorterapong and Moselhi (1996) for the backward pass, the author proposes the following more general equations to be used when the activities have lead/lag relationships (Refer to Figure 3.12). Equation (3-52) may be replaced by equation (3-57):

$$PLF_X = \underset{s \in S}{\widetilde{\min}} \begin{Bmatrix} FLF_s \ominus FF_{xs} \\ or \\ FLS_s \ominus FS_{xs} \end{Bmatrix} \tag{3-57}$$

Equation (3-52) corresponds to the second case of equation (3-57), where the lag time $FS_{xs} = 0$. If there is neither a FF_{xs} nor a FS_{xs} lag time relationship, then equation

(3-58) replaces equation (3-57). Equation (3-58) can be used when it is not possible to calculate a PLF_x. In this case it is necessary to calculate a preliminary late start (PLS_x). The definition of PLS is analogous to the late start time used in CPM.

$$PLS_X = \underset{s \in S}{\tilde{\min}} \begin{Bmatrix} FLS_s \Theta SS_{xs} \\ or \\ FLF_s \Theta SF_{xs} \end{Bmatrix} \tag{3-58}$$

Equations (3-59) to (3-61) replace equations (3-54) to (3-56), respectively.

$$FES_x \oplus Y \subseteq FLS^u \tag{3-59}$$

$$FLS_x = FES_x \oplus Y \tag{3-60}$$

$$FLF_x = FLS_x \oplus FD_x \tag{3-61}$$

In the case of interruptible activities equation (3-56) may be replaced by equation (3-62):

$$FLF_x = FLS_x \oplus FD_x \oplus FI_x \tag{3-62}$$

3.8.1.2 Criticality Measurement

In addition to the fuzzy scheduling results of fuzzy early and late times calculated in the previous section, the FNET method proposed by Lorterapong and Moselhi (1996), also calculates the degree of criticality of project activities and an approximate total float for each activity. The concepts of possibility measure and agreement index are used to measure the criticality of project activities.

Lorterapong and Moselhi (1996) employ the possibility measure and agreement index as tools in measuring the criticality of project activities. These tools were implemented due to the fact that the determination of the degree of criticality of project activities, when the durations are estimated with uncertainty, is not as obvious as in the case where they are estimated with certainty. The following steps indicate how the concepts of possibility measure and agreement index are used to measure the criticality of project activities:

- Step 1: Calculate the duration for each path in the project network:

$$T_x = \sum_{x \in X} FD_x \qquad (3\text{-}63)$$

Where x = an activity that belongs to path X

T_x = Duration of path X

FD_x = Fuzzy duration of activity x

As mentioned before, equation (3-63) was also conceived by Lorterapong and Moselhi (1996) to be used solely on projects where the relationship between activities is finish-to-start, with no time lag. Differing from the methodology proposed by Lorterapong and Moselhi (1996), the author proposes the following more general equations to be used when the activities have lead/lag relationships. Figure 3.11 illustrates all variables employed in the calculations.

Equation (3-64) can be used when the lag time between the predecessor activity p, and activity x is finish-to-start FS_{px}. Equation (3-63) corresponds to equation (3-64)

when the time lag FS_{px} = 0, and when the interruption on the predecessor activities p, FI_p = 0, and the interruption on activity x, FI_x = 0.

$$T_x = \sum_{\substack{x \in X \\ p \in X}} (FD_p + FI_p + FD_x + FI_x + FS_{px}) \tag{3-64}$$

Equation (3-65) can be used when the lag time between the predecessor activity p, and activity x, is finish-to-finish FF_{px}. (Refer to Figure 3.11).

$$T_x = \sum_{\substack{x \in X \\ p \in X}} (FD_p + FI_p + FF_{px}) \tag{3-65}$$

Equation (3-66) can be used when the lead time between the predecessor activity p, and activity x, is start-to-start SS_{px}. (Refer to Figure 3.11).

$$T_x = \sum_{\substack{x \in X \\ p \in X}} (SS_{px} + FD_x + FI_x) \tag{3-66}$$

Equation (3-67) can be used when the lead time between the predecessor activity p, and activity x, is start-to-finish SF_{px}. The start-to-finish relationship includes the fuzzy durations of the activities. (Refer to Figure 3.11).

$$T_x = \sum_{\substack{x \in X \\ p \in X}} SF_{px} \tag{3-67}$$

- Step 2: Once the duration of each path is calculated in step 1, the possibility measure between each path and the most critical path of the project is determined.

• Step 3: The agreement index for each path duration, T_x, and that of the most critical path in the project, T_{CP}, is determined.

$$AI(T_X, T_{CP}) = \frac{(areaT_X \cap T_{CP})}{areaT_X} \tag{3-68}$$

The maximum value that the PM and AI can achieve is 1. The most critical path in the project has PM and AI values equal to 1. If the PM and AI values between a certain path and the most critical path in the project are close to 1, this indicates that this path is near-critical.

• Step 4: The criticality of each activity is determined. Activities that belong to only one path, assume their possibility measure and agreement index from that path. For activities that belong to more than one path, the possibility measure of the activity takes the largest possibility measure of those paths. Similarly, the agreement index measure of the activity takes the largest agreement index of the paths to which the activity belongs. The agreement index is not applicable for activities that have crisp durations, due to the fact that the area of a crisp duration is zero.

• Step 5: The cumulative degree of criticality of each activity is determined. For activities that are common to more than one path, the cumulative degree of criticality is calculated as the summation of each possibility measure, and the summation of each agreement index for all the paths to which the activity belongs. If an activity belongs to a large number of paths in a network, then it will tend to have a higher cumulative degree of

criticality than those activities present on a smaller number of paths (Lorterapong and Moselhi, 1996).

3.8.1.3 Total Float

The approximate total float for each activity on the project is determined as the difference between the geometric centroids of the fuzzy early and late times. (Lorterapong and Moselhi, 1996). The geometric centroid, *C*, of a trapezoidal fuzzy number represented by the quadruple (*a, b, c, d*), can be calculated as follows:

$$C = \frac{-a^2 - b^2 + c^2 + d^2 - ab + cd}{3(-a-b+c+d)} \tag{3-69}$$

In the case of triangular fuzzy numbers ($b = c$), equation (3-70) can be used:

$$C = \frac{-a^2 + d^2 - ab + bd}{3(-a+d)} \tag{3-70}$$

The total float of activity x, can be computed as:

$$TF_x = C_x^{FLS} - C_x^{FES} \tag{3-71}$$

$$TF_x = C_x^{FLF} - C_x^{FEF} \tag{3-72}$$

Where C^{FLS} = Fuzzy late start centroid

C^{FES} = Fuzzy early start centroid

C^{FLF} = Fuzzy late finish centroid

C^{FEF} = Fuzzy early finish centroid

The eighth component of the fuzzy logic model is concluded with the calculations of the degree of criticality of project activities and the approximate total float for each activity. The reader may refer to Appendix A, were an example project is presented in order to illustrate the procedure to forecast progress at completion.

3.9 Effects of Delays on the Schedule

This section describes the seventh component of the fuzzy logic model that analyzes the effects of delays on the schedule. Project delays are caused by the accumulated impact of delays in individual activities. When an activity is delayed, this situation will have a certain effect upon succeeding activities. Delays may occur in any or all the activities, even though such delays may partially, fully, or not modify the project completion date. The purpose of this portion of the fuzzy logic model is to identify which activities contribute to the overall project delay and in which manner these delays affect the schedule.

3.9.1 Factors that determine the Effects of Delays on the Schedule

Consideration is given to the following factors when determining the effect of individual delays on the schedule:

- Delay type.
- The fact that activities are critical or non-critical in the actual schedule.
- Whether there is float to absorb the effect of delays.

Section 3.4.2 describes how delay types are determined in this fuzzy logic model (i.e. Type 1, Type 2, Type 3). Delay types are established with respect to their occurrence within the activity (i.e. an activity may be delayed due to a delayed start or extended activity duration).

The combined effect of the above mentioned factors can lead to the situations described in Table 3.8, that determine if a delay is critical to the completion date of the project:

Table 3.8 Effects of Delays on the Schedule

- A Type 1 delay on a critical activity that has the effect of delaying the project completion date.
- A Type 2 delay on a critical activity that has the effect of delaying the project completion date.
- A Type 3 delay on a critical activity that has the effect of delaying the project completion date.
- Any possible combination of sequential types of delays on a critical activity that has the effect of delaying the project completion date.

- A Type 1 delay on a critical activity that does not have the effect of delaying the project completion date.
- A Type 2 delay on a critical activity that does not have the effect of delaying the project completion date.
- A Type 3 delay on a critical activity that does not have the effect of delaying the project completion date.
- Any possible combination of sequential types of delays on a critical activity that does not have the effect of delaying the project completion date.

- A Type 1 delay on a non-critical activity that has the effect of delaying the project completion date due to the fact that the entire float available was consumed and did not absorb the effect of the delay.
- A Type 2 delay on a non-critical activity that has the effect of delaying the project completion date due to the fact that the entire float available was consumed and did not absorb the effect of the delay.
- A Type 3 delay on a non-critical activity that has the effect of delaying the project completion date due to the fact that the entire float available was consumed and did not absorb the effect of the delay.
- Any possible combination of sequential types of delays on a non-critical activity that has the effect of delaying the project completion date due to the fact that the entire float available was consumed and did not absorb the effect of the delay.

- A Type 1 delay on a non-critical activity that does not have the effect of delaying the project completion date, due to the fact that the whole float available or part of it was sufficient to absorb the effect of the delay.
- A Type 2 delay on a non-critical activity that that does not have the effect of delaying the project completion date, due to the fact that the whole float available or part of it was sufficient to absorb the effect of the delay.
- A Type 3 delay on a non-critical activity that does not have the effect of delaying the project completion date, due to the fact that the whole float available or part of it was sufficient to absorb the effect of the delay.
- Any possible combination of sequential types of delays on a non-critical activity that that does not have the effect of delaying the project completion date, due to the fact that the whole float available or part of it was sufficient to absorb the effect of the delay.

A delay on a critical activity does not have the effect of delaying the project completion date when a concurrent critical or non-critical activity is also delayed to such an extent that it creates float for the activity under consideration and it causes it to become non-critical to the project. For this reason the delay on an activity that was previously critical is not considered to delay the actual project completion date.

A non-critical activity does not delay the project completion date when the whole float available or part of it was sufficient to absorb the effect of the delay. In this case, the degree of critically of the activity increases as the amount of float available decreases. In spite of that, the activity is only considered to delay the project completion time, when it gets to the point that the float is consumed completely and it becomes critical to the project.

3.9.2 Analysis of the Effects of Delays

The user updates the project schedule whenever delays occur. The updated schedule produced using the FNET methodology contains fuzzy actual start and finish times of the activities, as well as an assessment of the criticality of project activities. The next step in the analysis is to determine if the delay that affected a particular activity had the effect of modifying the network logic (i.e. by generating new critical paths or shifting the critical path), and/or if it had the effect of delaying the project completion date.

This analysis is done by comparing previous and updated versions of the schedule. The first step is to determine if the criticality status of each delayed activity has changed (i.e. previously was non-critical and then became critical) due to the delay, and to establish the reasons that generated this event (i.e. the available float was consumed and did not absorb the effect of the delay). Based on the Type of delay determined in the

second component of the fuzzy logic model, the effect of the delay on the schedule is classified as one of the situations described in Table 3.8.

The same comparison process is repeated on the other activities on the project, since they may or may not be affected by the delay (i.e. the extended duration of an activity may push back the starting date of its successor activities).

The purpose of this analysis is to determine precisely the effect of each delay, not only on the activity it affected, but also on all project activities and on the project completion date. The importance of this analysis is that whenever delay claims and disputes arise, the contractor is able to prove exactly which delays modified the project completion time; and is also able to justify the reasons why certain delays did not have the effect of delaying the project completion date, but affected successor activities on the project.

The reader is referred to Appendix A, where an example project is to illustrate the situations described and how delays on activities affect the project completion date.

3.10 Consequences of Delays

This section presents the eighth and final component of the fuzzy logic model, which analyses the consequences of delays. Delaying events may cause a number of variations in a project, including late completion and the requirement of an acceleration of the work in order to meet the original completion date. The project manager may be required to accelerate the works thus modifying productivity and efficiency rates, or change the sequencing of the activities in the schedule to be able to reduce the impact of delays.

The purpose of this portion of the fuzzy logic model is to present the project manager with the likely consequences of delays on activity progress. Based on the project manager's analysis and assessment of the delaying events and their effect upon the schedule, he or she can focus his or her efforts on re-planning remaining progress by re-sequencing and accelerating activities. The reader is referred to Appendix A, where an example project is presented in order to illustrate how the fuzzy logic model analyses the consequences of delays.

The outputs produced by the fuzzy network schedule methodology described in Section 3.8 give the actual state of activities and provides the project manager with an actual project completion date. This information is stored in the Projected and As-Built section of the as-built database described in Section 3.3.1.4. If due to delays the actual project completion time is unacceptable, the project manager must determine the options available to diminish the effect of delays.

The project manager can then incorporate in the fuzzy logic model the measures he or she will take in order to reschedule the work so as to avoid delays. This is done by modifying the information contained in the Projected and As-Built section of the as-built database. The schedule is recalculated based on the revised durations and logic indicated by the project manager. This new result provides the project manager with a basis to determine if his or her measures were sufficient to put the work back on schedule. A description of the possible modifications to the schedule are provided in the following sections.

3.10.1 Acceleration

Acceleration is defined by Kraiem (1984) as "the advancement of the percentage of completion of a project ahead of the percentage required by the original construction schedule as properly adjusted for delays". Acceleration can be considered as a mechanism of putting lagging work back on schedule (Rubin, 1999).

Whenever the project manager is compelled by delaying circumstances, he or she may be required to accelerate the performance of the works in order to mitigate the impact of delays. In order to accelerate the works and thus reduce the durations of certain activities, the project manager may use such measures as: hiring of additional workers, working overtime and on weekends, acquiring additional and better equipment, and/or accelerating material delivery schedules.

In order to incorporate this measures in the schedule, the project manager may decrease the original duration of the activities in the fifth component of the fuzzy logic model that revises activity durations. The project manager decreases the duration of the remaining duration of the activity, so that the schedule is recalculated and updated to reflect the effect of the accelerated activity durations in the completion date of the project.

3.10.2 Rescheduling and Resequencing

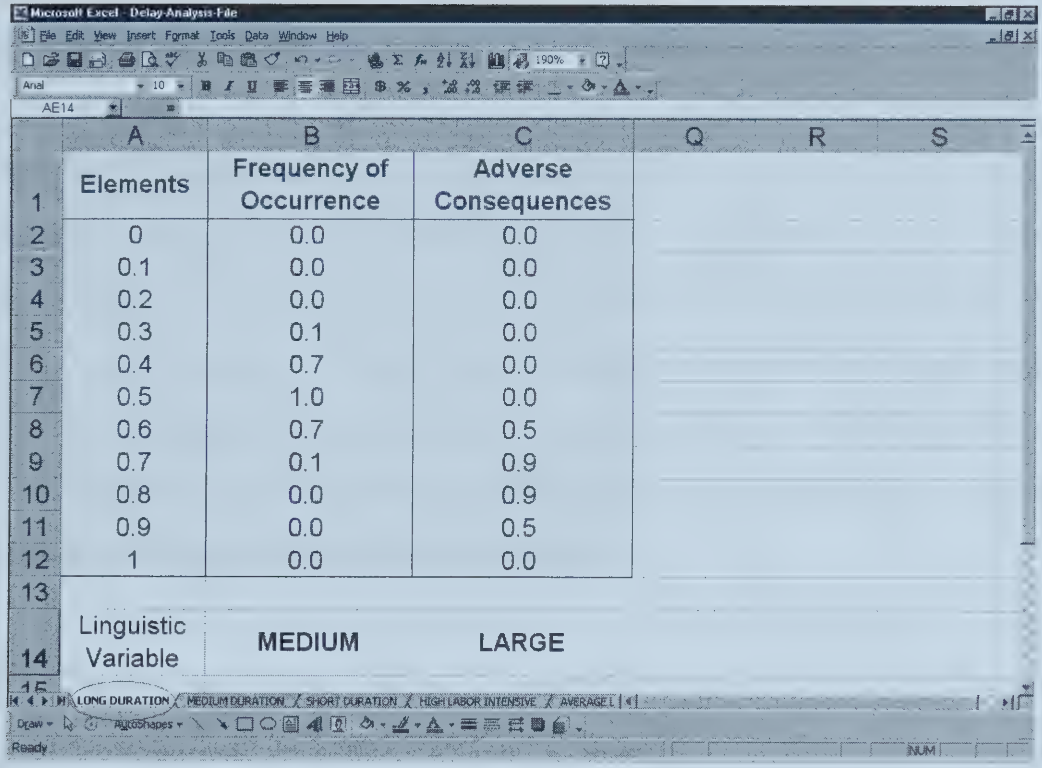
Subsequent to the occurrence of delays, the contractor may make revisions to the project schedule in an attempt to minimize the impact of delays and make up for lost time. In order to do this, contractors may resequence activities, reschedule major portions of the work, correct logic errors, or revise work sequences to reflect concurrency of activities. Rescheduling may be required only on the activities directly affected by delays, even though preceding activities may also be resequenced. Resequencing the project

schedule may help to absorb lost time and diminish the impact of delays upon the overall project completion.

3.11 Computer Implementation

The methodology to estimate delay durations described in Section 3.5 was implemented in the form of a computer program. The program consists of two components linked together. The first component is implemented in MS Excel, and is used to store the information related to the membership function values employed in the methodology. The second component of the program is implemented in MS Visual Basic 6.0, and utilizes the information stored in MS Excel to perform the calculations of the methodology. The user follows the next steps in order to assess a delay duration:

- Step 1: For each activity experiencing a delay, the user determines the relevant delay sensitive attributes and the corresponding states of each attribute in linguistic terms. The file in Excel is composed of a number of spreadsheets, each representing a particular delay-sensitive attribute state. The user creates one spreadsheet to store the membership functions for each attribute state. For instance, if the duration of a delay is being evaluated using three delay-sensitive attributes, each described by three states, then the total number of spreadsheets in the file is nine. A new attribute state can be added by inserting a new spreadsheet in the Excel file. The name of this spreadsheet is the same as that of the attribute state that it represents (i.e. "Long Duration"). Figure 3.14 shows a sample spreadsheet for a delay-sensitive attribute state. As can be seen, the name of the spreadsheet is circled, and it corresponds to "Long Duration".



Elements	Frequency of Occurrence	Adverse Consequences
0	0.0	0.0
0.1	0.0	0.0
0.2	0.0	0.0
0.3	0.1	0.0
0.4	0.7	0.0
0.5	1.0	0.0
0.6	0.7	0.5
0.7	0.1	0.9
0.8	0.0	0.9
0.9	0.0	0.5
1	0.0	0.0
Linguistic Variable	MEDIUM	LARGE

Figure 3.14 Sample Spreadsheet for a Delay-Sensitive Attribute State

• Step 2: For each spreadsheet representing a particular attribute state, the user inputs the frequency of occurrence and the adverse consequences expressed in linguistic terms and their corresponding membership values. This inputs are produced by the user because they are based on the characteristics of the project and the situation that originated the delay, and they reflect the user's subjective assessment of the problem. The program combines the frequency of occurrence and adverse consequences for each attribute state in each spreadsheet. This is done by calculating the fuzzy relation *R*

between the fuzzy set *F*, representing the frequency of occurrence, and the fuzzy set *C*, representing the adverse consequences.

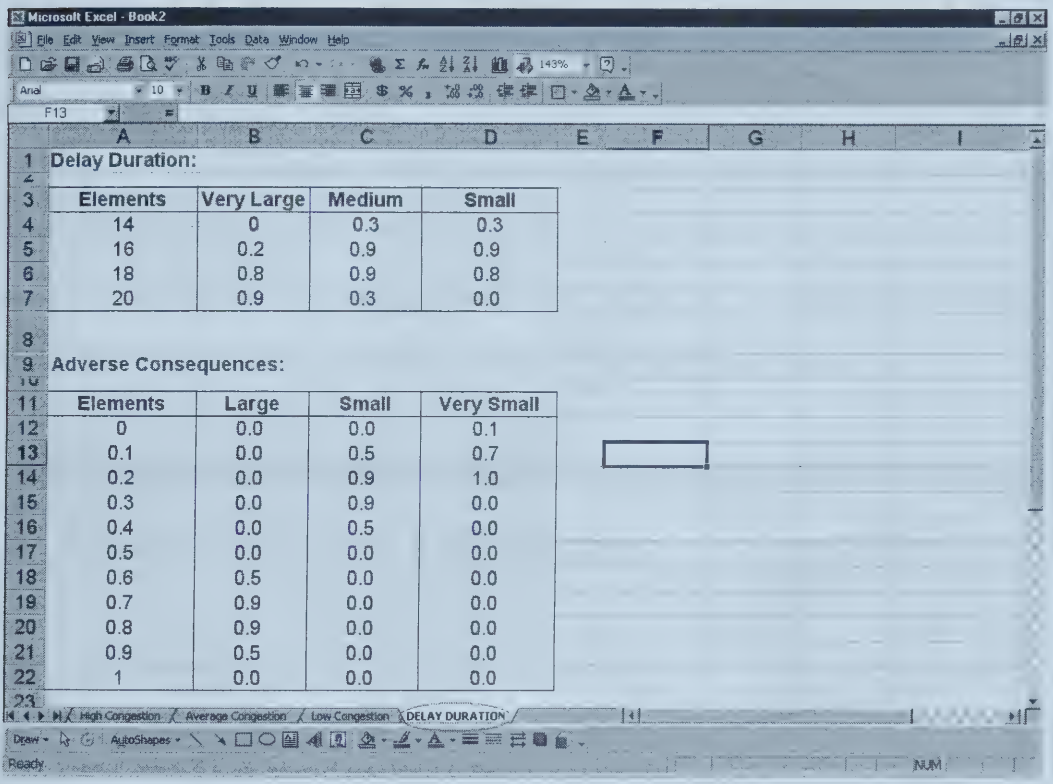
The corresponding frequency of occurrence and the adverse consequences expressed in linguistic terms and in membership values for the delay attribute “Long Duration”, can also be seen Figure 3.14. Other delay-sensitive attribute states spreadsheets can be observed Figure 3.14: "Medium Duration", "Short Duration", and "High Labour Intensive". The user may add as many delay-sensitive attribute states spreadsheets as he or she considers will affect the impact a delay will have on an activity. The Visual Basic component of the program will use in its calculations any number of spreadsheets that the user includes in the Excel file.

- Step 3: The user inputs the adverse consequences and the delay duration expressed in linguistic terms and their corresponding membership values. This inputs reflect the user's subjective judgment of the delay duration. The program combines the adverse consequences and delay duration. This is done by calculating the fuzzy relation *Q* between the fuzzy set *C*, representing the adverse consequences, and the fuzzy set *D*, representing the delay duration.

The last spreadsheet of the Excel file is called "Delay Duration" and it contains the information related to the delay duration and how it is affected by the adverse consequences. Figure 3.15 shows a sample spreadsheet for delay duration. As can be seen, the name of the spreadsheet is circled, and it corresponds to "Delay Duration". In the delay duration spreadsheet, the user inputs the adverse consequences and the delay duration expressed in linguistic terms and their corresponding membership values.

As can be seen in Figure 3.15, the user established the following relation between the adverse consequences and the delay duration: "If the delay duration is very large,

then the adverse consequences are large, if the delay duration is medium, then the adverse are small, If the delay duration is small, then the adverse are very small".



Delay Duration:

Elements	Very Large	Medium	Small
14	0	0.3	0.3
16	0.2	0.9	0.9
18	0.8	0.9	0.8
20	0.9	0.3	0.0

Adverse Consequences:

Elements	Large	Small	Very Small
0	0.0	0.0	0.1
0.1	0.0	0.5	0.7
0.2	0.0	0.9	1.0
0.3	0.0	0.9	0.0
0.4	0.0	0.5	0.0
0.5	0.0	0.0	0.0
0.6	0.5	0.0	0.0
0.7	0.9	0.0	0.0
0.8	0.9	0.0	0.0
0.9	0.5	0.0	0.0
1	0.0	0.0	0.0

Figure 3.15 Sample Spreadsheet for Delay Duration

Step 4: The program calculates the union matrix, *T* that represents the relationship between the frequency of occurrence set, *F*, and the adverse consequences set, *C*. The program calculates the union matrix *V* that represents the relationship between the adverse consequences set, *C* and the delay duration set, *D*. The program calculates the composition matrix $T_{o}V$ that relates fuzzy sets *F*, and *D*, through their respective relationship to a third common set, fuzzy set *C*.

• Step 5: The user executes the Visual Basic component of the program. Figure 3.16 shows the interface of the program that displays the contents of the Delay-Sensitive Attribute State Spreadsheet, and the Delay Duration Spreadsheet. The user can scroll between delay-sensitive attribute states. The elements and the membership function values related to a given linguistic variable for a given attribute state will be displayed on the screen. For each attribute state the user can observe the membership functions of the frequency of occurrence and the adverse consequences, corresponding to fuzzy relation *R*. The user can also observe the membership functions of the adverse consequences and the delay duration, corresponding to the fuzzy relation *Q*.

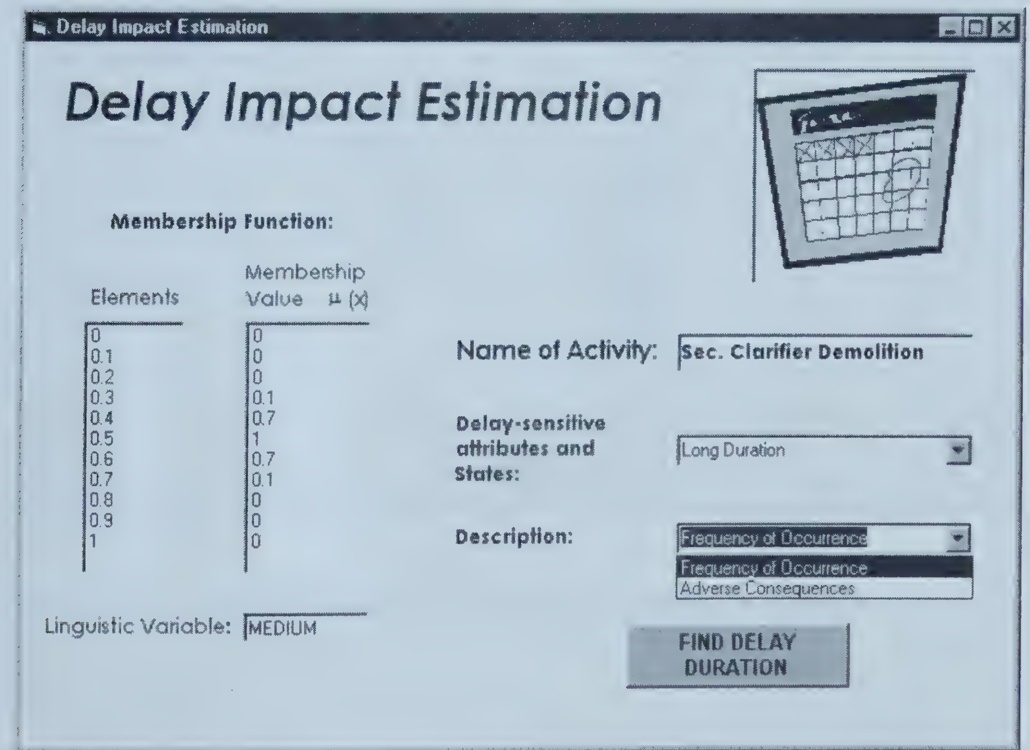


Figure 3.16 Visual Basic Interface of the Delay Impact Estimation Program

When the user presses the button "Find Delay Duration", so that the program performs the calculations of the delay impact estimation method.

• Step 6: The program displays the results of the calculations performed. Figure 3.17 shows the results of the delay impact estimation analysis by displaying the mean and standard deviation of the delay duration, and the frequency of occurrence of the elements in the delay duration. (i.e. the probability density function).

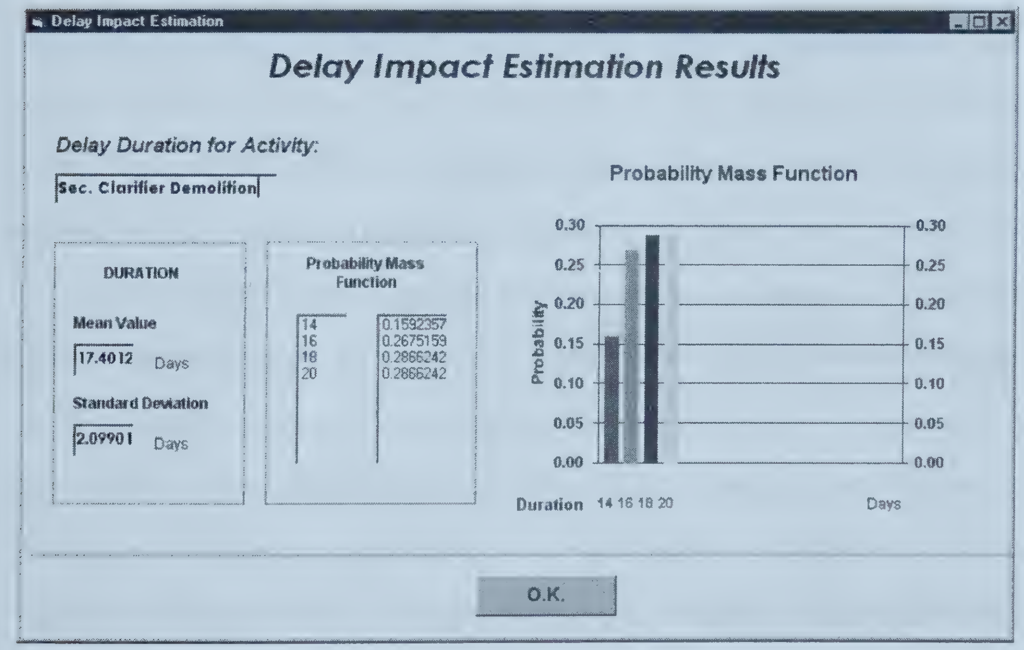


Figure 3.17 Results Produced by the Delay Impact Estimation Program

3.12 Summary

Whenever a delaying event is identified as impacting the normal progress of an activity, the fuzzy logic model described in this chapter can aid in the analysis of the subsequent effect of the delay on the completion date of the project. The first step involves the documentation of the appropriate information into the as-built database concerning the activity being analyzed. This information is interpreted by the fuzzy logic model to update the schedule in terms of actual start and finish dates. Among the information related to delaying events, the database contains lists of potential causes of delays that the project manager can use by relating them to the occurrence of delays. The next portion of the fuzzy logic model assists in the categorization of delays by utilizing a cause/effect matrix that relates the causes of delays with their corresponding responsibility that leads to the proper categorization of the type of delay under analysis.

The next stage of the fuzzy logic model allows the estimation of the anticipated duration of the delaying impact by determining it corresponding delay-sensitive attributes, and by producing qualitative assessments about the frequency of occurrence and adverse consequences regarding the delay, utilizing fuzzy sets and fuzzy relations. The methodology to estimate delay durations was implemented in the form of a computer program. The delay duration is transformed into a triangular fuzzy number and the original activity duration is revised and increased to account for the occurrence of the delay. The succeeding portion of the schedule is recalculated and updated in terms of fuzzy early and late times, and a new actual project completion date is obtained.

The next step is the determination of the effects of delays on the schedule by evaluating the previous and actual state of activities with respect to criticality, in order to establish if they have the effect of altering the project completion date. With this

knowledge in mind, the project manager can analyze the actual status of the schedule. If he or she is not in agreement with the actual completion time and wishes to find means to recover the lost time and diminish the effects of delay, the last portion of the fuzzy logic model can be used. The project manager can modify or alter the projected schedule by decreasing the duration of activities by means of accelerating the works and/or by resequencing the activities. Based on the measures taken by the project manager, the schedule is recalculated, and the effectiveness of the corrective actions taken can be assessed based on the resulting schedule.

Appendix A presents an example project to illustrate the fuzzy logic model developed in this chapter.

CHAPTER 4 DATA COLLECTION FOR CASE STUDY: BIOREACTORS UPGRADE

4.1 Project Description

A case study of an actual project was used to collect the necessary information to test the performance of the fuzzy logic model dedicated to construction daily site recording and progress forecasting.

The project consisted of retrofitting existing Bioreactors and Secondary Clarifiers of a local wastewater treatment plant. The work in the Bioreactors included the installation of mechanical equipment (i.e. aeration system, mixer and mixer pumps); supply and installation of associated piping, gates, electrical controls in tanks and galleries; demolition of concrete walls; and construction of concrete baffle walls and chambers. The work in the Secondary Clarifiers involved the installation of gates and piping, modification to return rails on sludge collection equipment, and cutting of access openings between clarifier bays.

4.2 Data Collection

The first step in data collection involved the creation of an as-built database, which allowed a large amount of information to be incorporated and analyzed automatically. In order to develop the as-built database, it was necessary to determine which project documents best provide the required information. In this case, bid documents and specifications, preliminary and as-planned schedules, scheduling updates and daily inspector site reports were the main sources of information. The information contained in the daily inspector site reports was reviewed, selected, analyzed, and sorted in order to accurately identify the actual progress observed in the

field. Interviewing the construction personnel involved with the actual construction was also helpful to understand the actual construction sequence and to identify delay issues.

Site visits to the project site were performed during the months of January to April, 2001. Data on project information was collected for the time period of October, 2000 to April, 2001. The analysis and processing of information in order to design and develop the as-built database and the as-built schedule, was carried out during the months of June to September, 2001. Different activities performed in order to collect the information are described in the following sections.

4.2.1 Site Visits

Various site visits were performed at different stages of the construction project in order to gain a better understanding of the project by identifying the different activities and construction processes, by observing and analyzing progress, and by understanding the logical sequence of the work. The site visits were carried out with the Engineer's inspector, who was involved in the actual construction. Notes relative to the sequence of the work were taken and analyzed subsequently.

4.2.2 Field Personnel Interviews

Interviews with field personnel were useful in understanding the logic of some complex construction operations and technical procedures. Field interviews were also very helpful in identifying problems that field personnel thought affected the normal progress of the works. The problems that field personnel identified were a valuable tool in analyzing the issues that generated delays.

4.2.3 Bid Documents Review

The project plans and specifications were reviewed and analyzed in order to get a more accurate understanding of the work involved. The purpose of this review was to gain a better understanding of major work components and the logical sequence that controlled work progress.

4.2.4 Scheduling Review

The preliminary schedule was reviewed to analyze activity durations, logic relationships between activities, critical paths, float, start and finish times of milestones and project completion dates. It was also verified that the general sequence of progress in the as-planned schedule was in accordance with that established in the contract documents, plans and specifications. Variations and/or sequencing errors were noted and examined before proceeding with the analysis. Different schedule updates were analyzed in order to determine the project status at specific points in time.

4.2.5 Review of Daily Inspector Site Reports

The inspector's daily reports were a valuable source to identify the work executed on a day-to-day basis as well as any problems and delays that impacted normal progress. These reports included a daily record of weather, location inspected each day, materials delivered, damaged materials or unsuitable supplies, types of equipment used and equipment breakdowns, trades and subcontractors working, progress, start of new operations, visitors, safety observations, topics covered in job meetings, participants that attended the meetings, status of change orders, information required from the owner or the contractor, status of shop drawing review, and the need for clarification of drawings or

specifications. The site reports also were helpful in identifying technical problems as well as the party liable for them.

4.3 Scope of the Analysis

The project includes the retrofitting of a total of ten tanks. Due to the magnitude of the project and the large volume of information to be processed, the scope of the present analysis was limited to the work undertaken on the first two Bioreactors and Secondary Clarifiers. The actual number of activities required to complete these two tanks was 75, the actual start date was October 10, the project duration was 155 days, and the actual project completion date was March 12, 2001. The scope of the analysis was further limited by including only the civil and mechanical portions of the work. The actual number of activities to complete this portion of the schedule was 40 activities, the actual start date was October 10, the project duration was 122 days, and the actual the project completion date was February 18, 2001.

4.4 Determination of Delays

The method employed to determine the amount of delay was to compare the contractor's as-planned schedule to the as-built schedule that contains actual completion dates for all activities. Once it has been determined that an activity has been delayed, a thorough review of the as-built information was performed to draw correct conclusions concerning the delay and its causes.

4.4.1 As-Planned Schedule

A careful decision was made in order to select the schedule that best represented the project as-planned schedule. The first schedule analyzed was the general contractor's preliminary schedule submitted with the contract documents. This schedule was submitted on October 31, 2000. A thorough review of this schedule based on the study of the information presented in Section 4.2, revealed that the schedule lacked the adequate level of detail needed for the analysis, and that the number of activities included in the schedule was insufficient (55 activities compared to 75) for the amount and complexity of the work.

According to this schedule, the work was scheduled to start on October 10, 2000 and to be completed on February 18, 2001. Since the actual project completion time was March 12, 2001, it was decided to adopt the next update schedule available as the as-planned schedule for the analysis. This schedule contained 66 activities and was submitted on December 6, 2000. The schedule was an updated version of the as-planned schedule, since no progress was registered on it. In accordance to this schedule, the project completion time was March 12, which coincided with the actual project completion time. The project started as planned on October 10, 2000.

Utilizing this schedule as a starting point, a detailed analysis proceeded. The first step was to identify and separate the civil and mechanical activities that correspond to the portion of the schedule under analysis, as was described in Section 4.3. It was noted that the schedule provided by the contractor was a bar chart where the activity names and durations were included. It contained very limited information with respect to the logical sequence of activities, and there was no definition of the critical path of the project. Different conclusions about the sequence of work and the interrelationships between

activities were deduced. To the greatest extent possible, every effort was made not to modify the judgment that the person who originally planned the schedule had in mind.

Logic relationships between activities were included in the schedule, so that it was possible to produce a CPM schedule for the project. This version of the schedule was named "original schedule" and Figure 5.1 is a representation of the bar-chart schedule corresponding to the "original schedule", and Figure 5.2 depicts the corresponding network representation. It can be seen that the project has two critical paths, one that is determined by the construction of concrete structures and the other one that is controlled by the installation of the aeration system.

The original schedule was then analyzed for logic and feasibility, and it was concluded that this version of the as-planned schedule still did not correctly portray the logic that was employed in constructing the actual project, the actual durations of activities, nor the number of activities actually performed. For instance it can be seen on Figure 5.1 that in the original schedule, the construction of some important concrete structures (activities 16 through 23) was not included.

As was mentioned in Section 4.3, the actual number of civil and mechanical activities that correspond to the portion of the schedule under analysis was 40, the total project duration was 122 days, and the actual completion date was February 18, 2001. As can be seen in Figure 4.1, the number of civil and mechanical activities included in the original schedule is 32, the portion of the schedule under analysis was scheduled to finish on December 23, 2000, and the total project duration was 75 days.

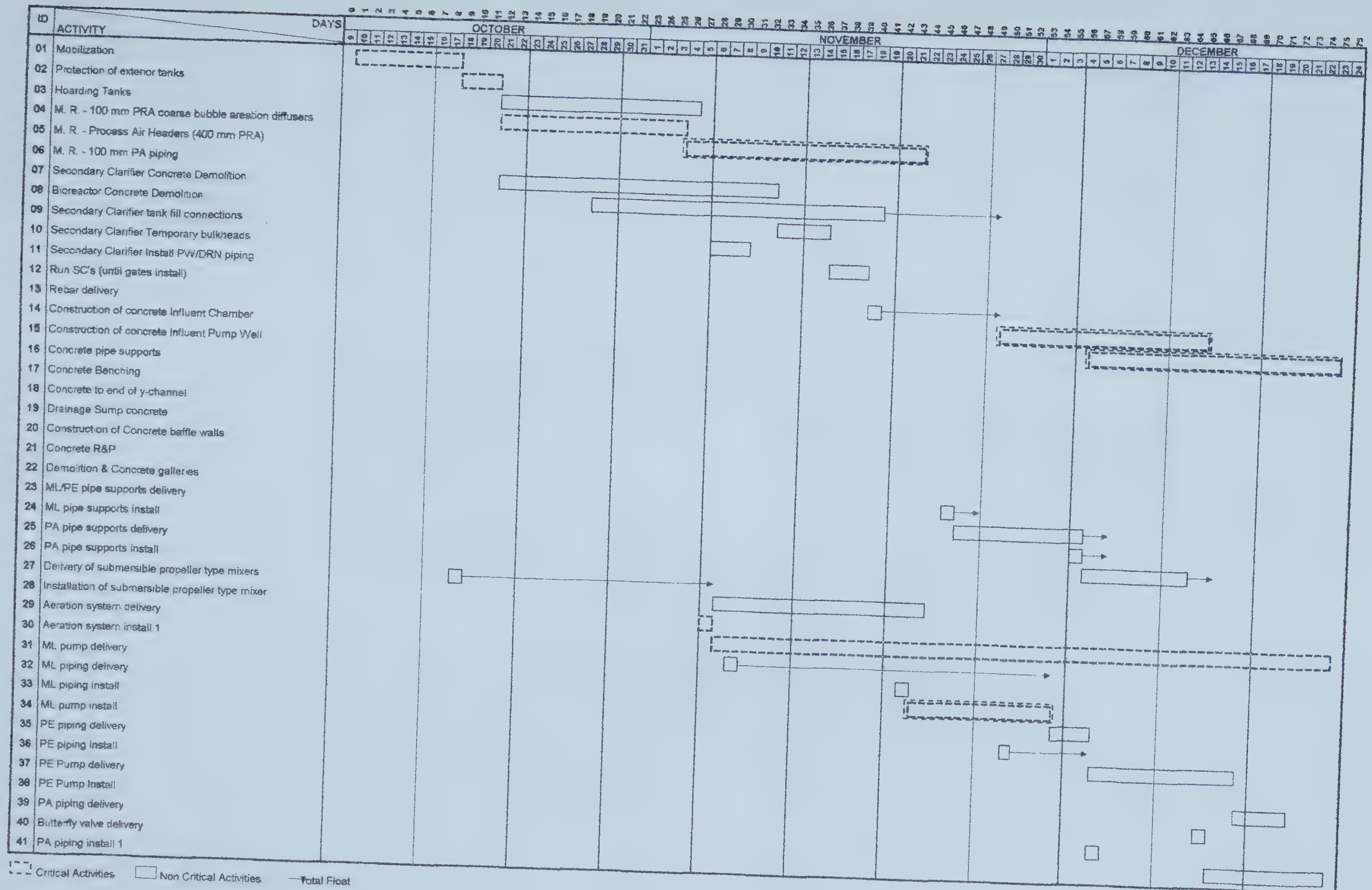
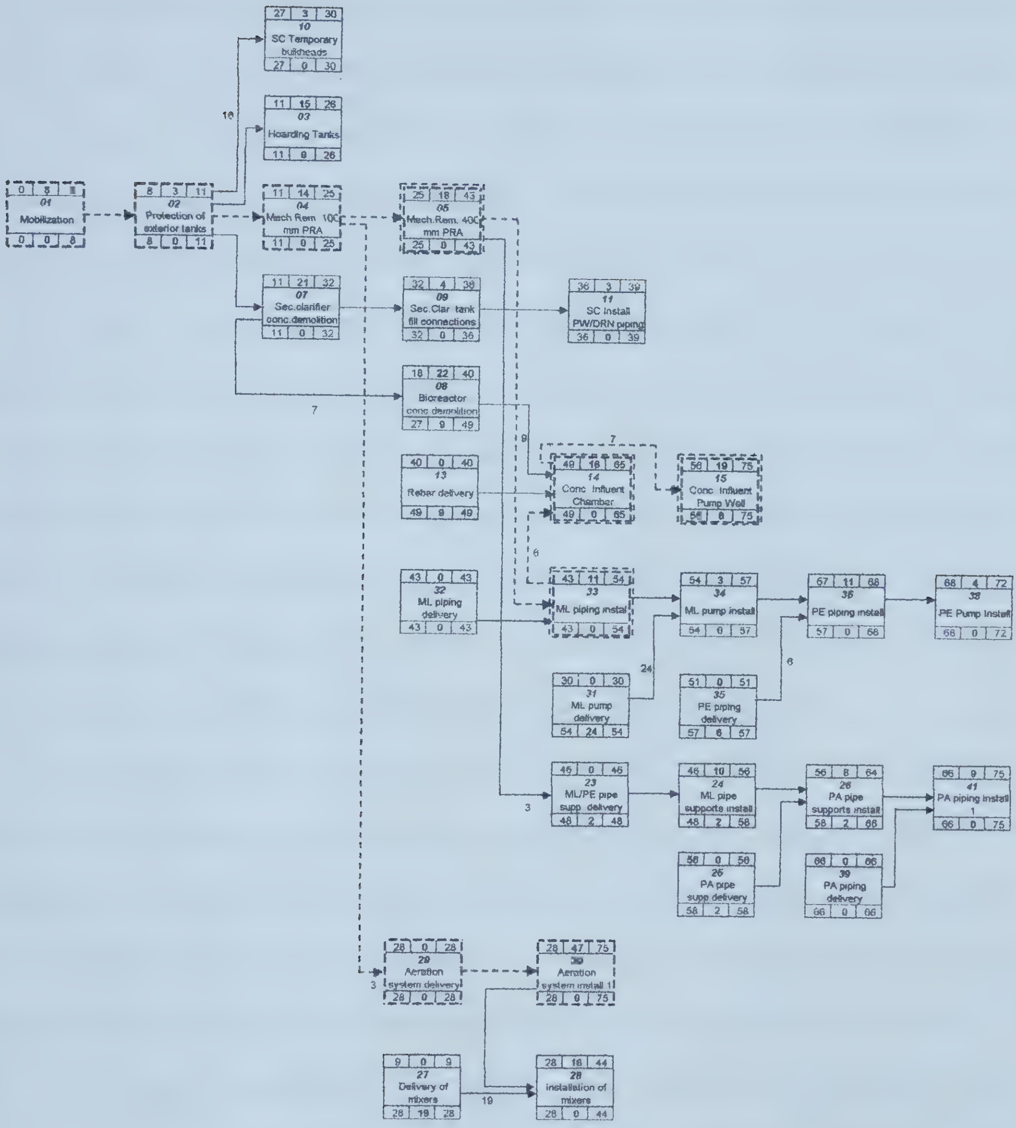


Figure 4.1 Bar Chart - Original Schedule for Case Study



Activities on Critical Path 1: 01 - 02 - 04 - 05 - 33 - 14 - 15

Activities on Critical Path 2: 01 - 02 - 04 - 29 - 30

Figure 4.2 Network Diagram - Original Schedule for Case Study

The conclusions reached with respect to the usefulness of the original schedule were based on a complete analysis of the information contained in the as-built database (refer to Section 4.3), that indicates the actual sequence of the work and the actual timing of the activities. The study of the different sources of project information revealed the fact that the original schedule required modifications to account for obvious omissions, so that the schedule correctly represented the initial plan for construction.

In order to overcome the shortcomings that diminished the usefulness of the schedule in the analysis, the original schedule was modified in order to create a more accurate schedule. These modifications were based on the various sources of project information described in Section 4.2, that clarified the thought process that went into defining the planned sequence of work. Practical knowledge of the project and the physical construction requirements were also necessary to reach reasonable conclusions about the project's logical sequence of construction and its critical path.

The schedule obtained after this process is depicted in Figures 4.3 and 4.4, and it constitutes the as-planned schedule and starting point of the analysis performed in Chapter 5. As can be observed, this project is scheduled to finish on February 8, 2001 and the total project duration is 122 days. It includes interruptions for the activities performed during the week of December 25 to 31, due to the Christmas break taken.

The original schedule has two critical paths, one that is determined by the construction of concrete structures and the other one that is controlled by the installation of the aeration system. Figure 4.4 shows that the as-planned schedule has two critical paths that are determined by the construction of the concrete structures. This paths, became the largest paths of the project after the addition of all the missing activities related to the construction of concrete structures (activities 16 through 23).

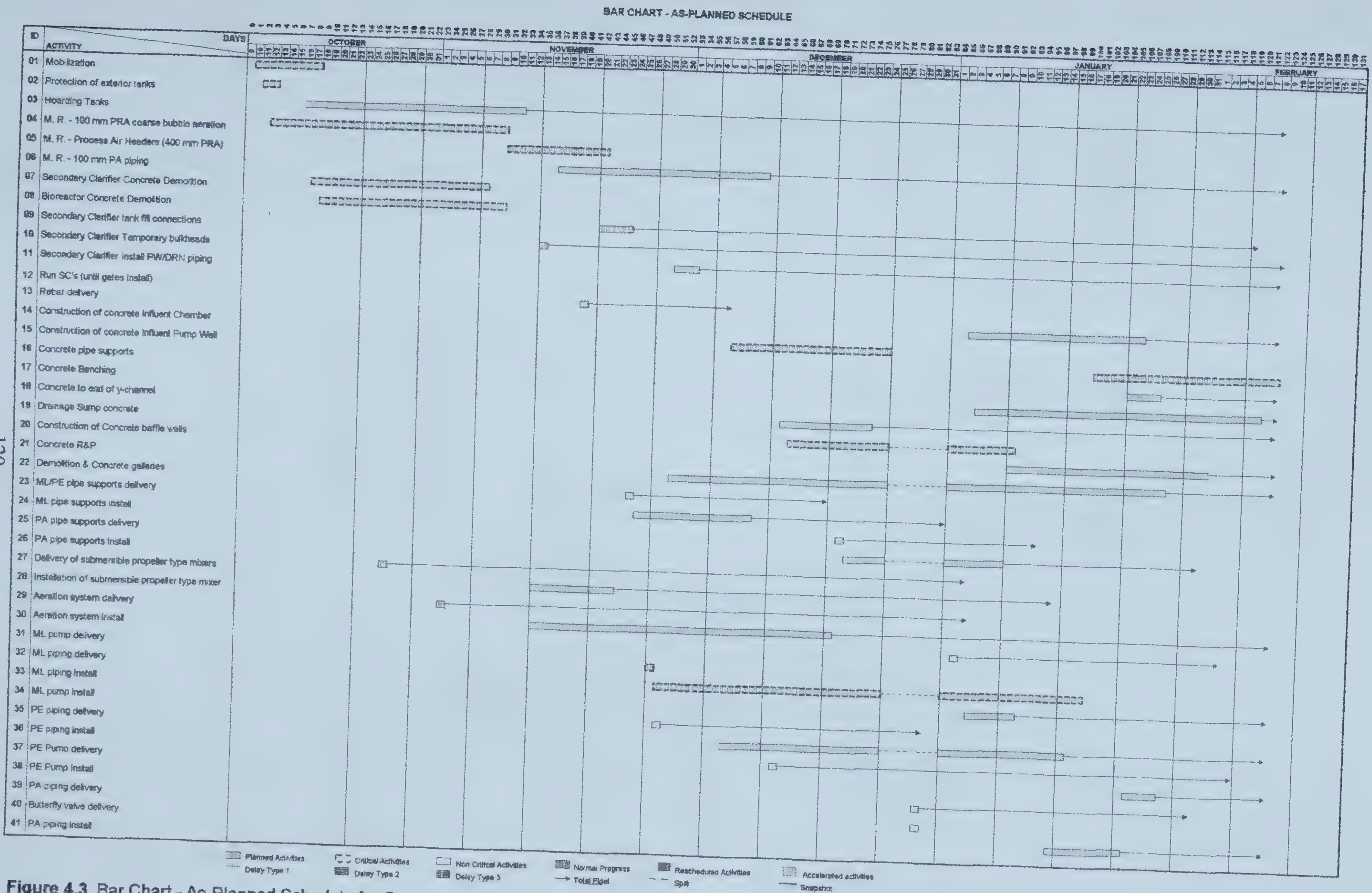
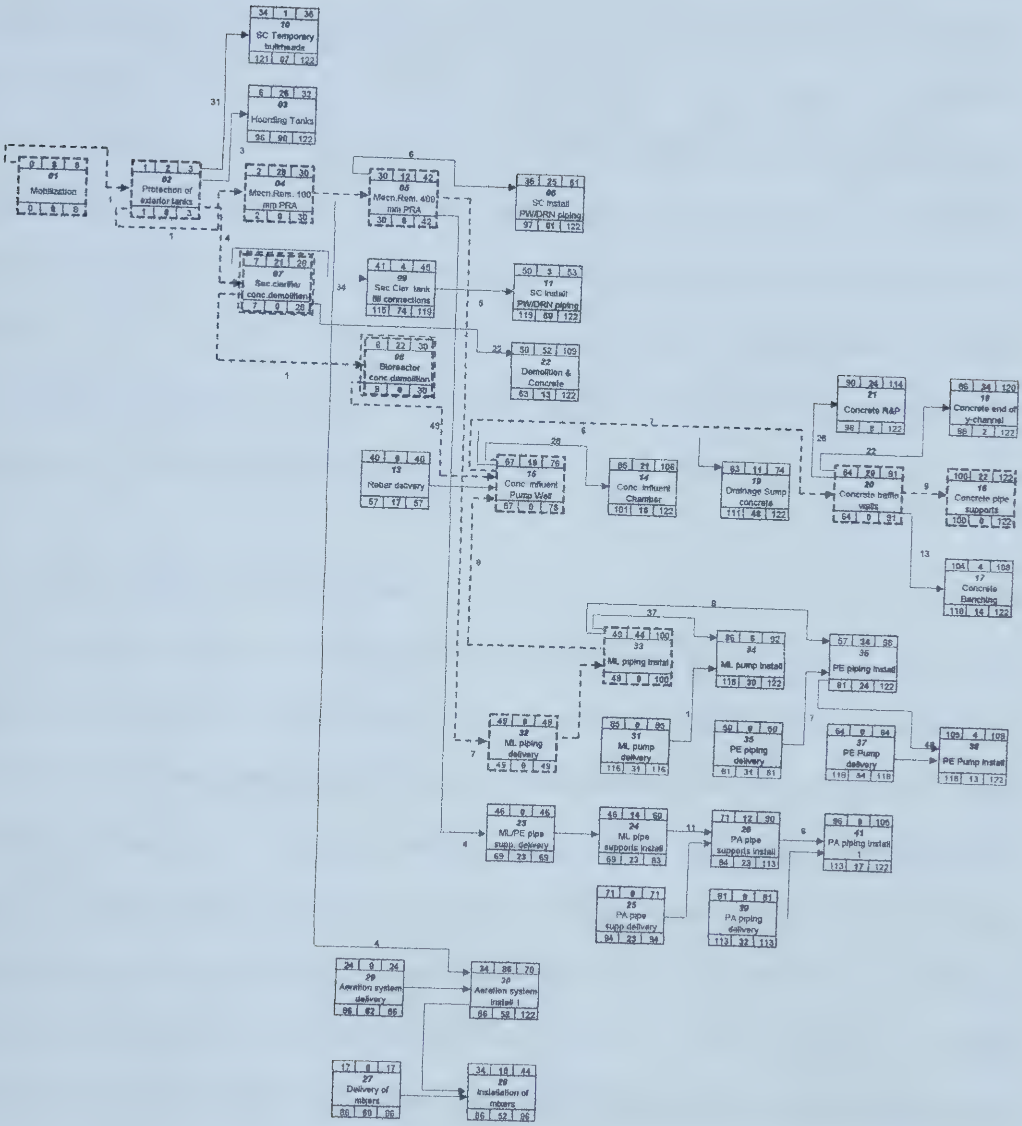


Figure 4.3 Bar Chart - As-Planned Schedule for Case Study



Activities on Critical Path 1: 01 - 02 - 07 - 08 - 15 - 20 - 16

Activities on Critical Path 2: 01 - 02 - 04 - 05 - 32 - 33 - 15 - 20 - 16

Figure 4.4 Network Diagram - As-Planned Schedule for Case Study

4.4.2 As-Built Schedule

Once the as-planned schedule was established, the next step was to prepare an as-built schedule. The foundation for the preparation of the as-built schedule is the as-built database. An as-built database was created for the project incorporating contemporaneous project documentation, in order to establish a detailed performance record of daily activities that correctly reflected project timing, sequence and progress. The creation of an as-built database can be divided into three steps; the design of the database structure, the transfer of information from contemporaneous project documentation into the database, and the extraction of the as-built schedule from the database. The as-built database was implemented in MS Access.

4.4.3 As-Built Database Structure

The main source of information that was collected and recorded in the as-built database, were the daily inspector site reports described in Section 4.2.5. The daily site reports provide a daily description of how work was actually performed on the site. Figure 4.5 shows a segment of a daily site report produced by the inspector of the case study project. As can be seen in Figure 4.5, the daily site report contains information on every daily task performed by each subcontractor. Each task corresponds to a particular activity in the as-planned schedule shown in Figure 5.3. The information on the task performed consists of the following data: area where the task was performed, description of the work, equipment used, trades present, materials delivered and general comments. The inspector also includes information related to the weather conditions of that particular day.

DAILY PROGRESS REPORT
October 21, 2000

October 21, 2000 (Saturday) +3 deg. C to +10 deg. C, windy

Activity: Subcontractor #1 - Continued to install 4x4s for hoarding on Bioreactor #2 – Bays A & B. Started to install rebar hoops for hoarding over Bay A on both Bioreactors #2 and #3. (1S, 5PF.) Continued to move old 100mm PRA piping to the south end of the bays in Bioreactor #2 for removal. Equipment: genset, drill.
Subcontractor #2 - Not on site today.
Subcontractor #3 - Continued coring to enlarge opening at Mixed Liquor (ML) slide plate gates into Clarifier #2 and Clarifier #3. Equipment: 3 gensets, 3 coring machines. (1S, 3Op)

Comment: Rebar delivered for Hoarding. Too windy to install tarp for hoarding over Bioreactor bays today. Removal of the existing baffle walls in the Clarifier will have to be done. (Removal of the wooden baffles was indicated on the contract drawings.).

Figure 4.5 Segment of a Daily Inspector Site Report

The structure of the database was derived from the information contained in the daily site reports, and was designed to store this information in an efficient and organized manner. Figure 4.6 depicts a schematic diagram of the database structure designed for the case study project. The database is comprised of six related tables. The Task Data table is the main table, and it is related by specific codes to the other tables in the database, so that commonly occurring data are stored only once.

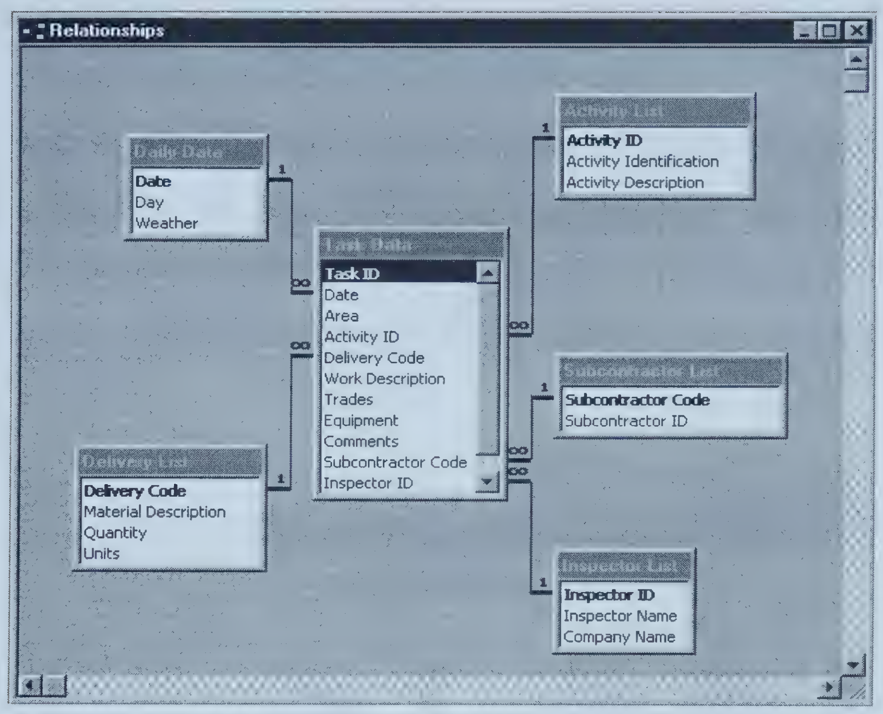


Figure 4.6 As-Built Database Structure

4.4.4 Transfer of Information into the Database

The as-planned schedule activity identification numbers were assigned to the corresponding Activity List table, in order to identify the as-built activities in a manner consistent with the activities in the as-planned schedule. This facilitated the process of comparing planned performance with the actual progress observed in the field.

The database contains one record for each daily task performed, corresponding to an activity on the schedule. Each record contains different fields of data to store specific information from the daily site reports. The information contained in the shaded items in Figure 4.5 coresponds to one task performed by one subcontractor on a

particular day. As an illustrative example, the process to transfer the shaded information shown in Figure 4.5 into the database, is explained as follows.

Figure 4.7, shows the main window used to enter daily activity information into the database. The "Daily Data" option is selected which displays the window shown in Figure 4.8. The information related to weather conditions on this particular day is entered in the "Daily Data" window, by entering the date, the day of the week and a description of the weather conditions.

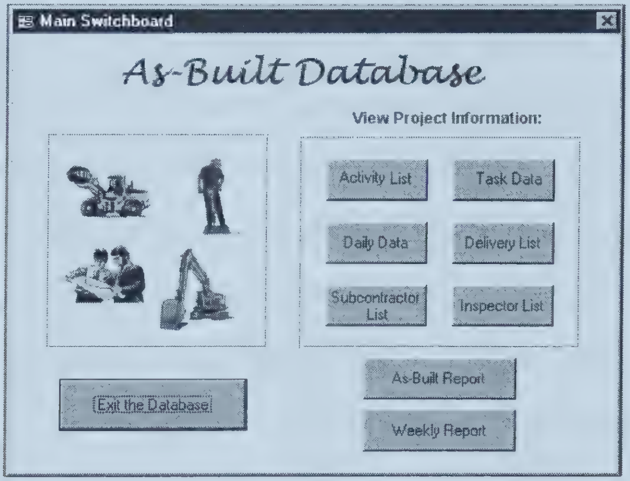


Figure 4.7 Main Window

[illegible]

[illegible]

[illegible]

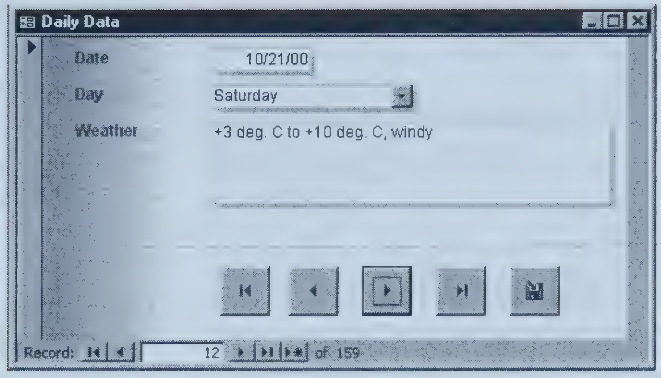


Figure 4.8 Daily Data

Next, the daily site report information describing the tasks performed on that day is analyzed to determine the activity to which the tasks correspond. The tasks are described in the "Activity" section of the report. As can be seen on the shaded items in Figure 4.5, two tasks were performed by the subcontractor #1. One task corresponds to the activity "Hoarding Tanks", and the other task corresponds to the activity "Mechanical Removals - 100 mm Process Air (PRA) coarse bubble aeration diffusers". The information related to each task is stored in separate records. The transfer of the information related to the task that corresponds to the activity "Hoarding Tanks" is described here. This information is shaded in the site report on Figure 4.5.

Next, activity "Hoarding Tanks" is added to the Activity List table of the database. The Activity List option is selected on the main window in Figure 4.7, and the window shown in Figure 4.9 is displayed. The activity identification number on the as-planned schedule for activity "Hoarding Tanks" is "3". This activity ID is entered on the Activity List window, as well as a full description of the activity.

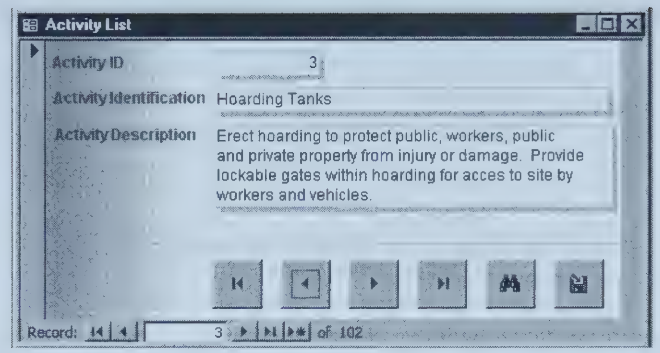


Figure 4.9 Activity List

The next step in the process is to enter the task information into the Task Data table of the database. The Task Data option is selected in the main window in Figure 4.7, and the window shown in Figure 4.10 is displayed. A task ID needs to be assigned to the task performed on the 21st of October, 2000. It has been determined that this is the sixth task that has been performed on activity No. 3, “Hoarding Tanks”, since it started. For this reason the last two numbers of the task ID are “06”, and the first number is “3”, which indicates that the task belongs to activity No. 3.

Specific fields of data are filled in with the information contained in the daily site report. The information consists of the date, area, work description, trades, equipment, report number and comments, and is transferred from the site report into the respective database fields.

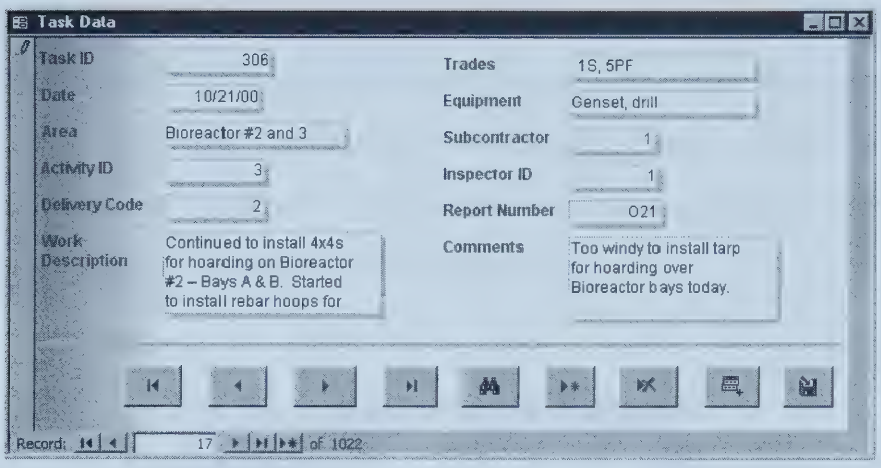


Figure 4.10 Task Data

The information on the subcontractor that performed the task is stored on the Subcontractor List table shown in Figure 4.11. This window is accessed by selecting the Subcontractor List option in the main window in Figure 4.7. A subcontractor code is assigned to each subcontractor that worked on site. The subcontractor code is the link between the Subcontractor List and Task Data tables.

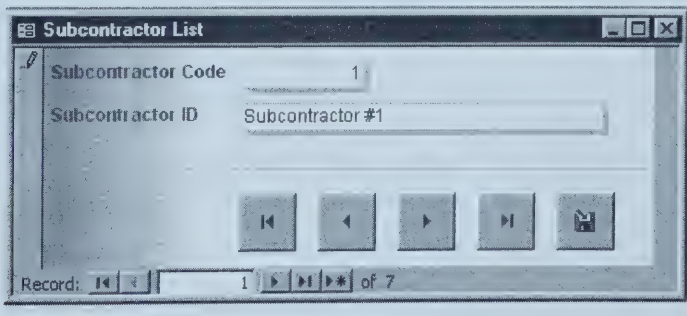


Figure 4.11 Subcontractor List

The information on the inspector on site is stored on the Inspector List table shown in Figure 4.12. This window is accessed by selecting the Inspector List option on the main window in Figure 4.7. An Inspector ID is assigned to each inspector on site. Information on the company and name of the inspector is also included. The Inspector ID is the link between the Inspector List and Task Data tables.

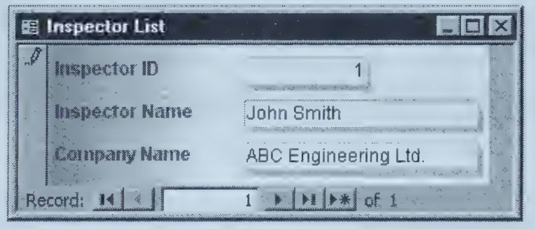


Figure 4.12 Inspector List

Information related to deliveries is stored in the Delivery List table shown in Figure 4.13. This window is accessed by selecting the Delivery List option in the main window in Figure 4.7. A Delivery Code is assigned to every delivery on site. Information on the material description, quantity and units is also included. The Delivery Code is the link between the Delivery List and Task Data tables.

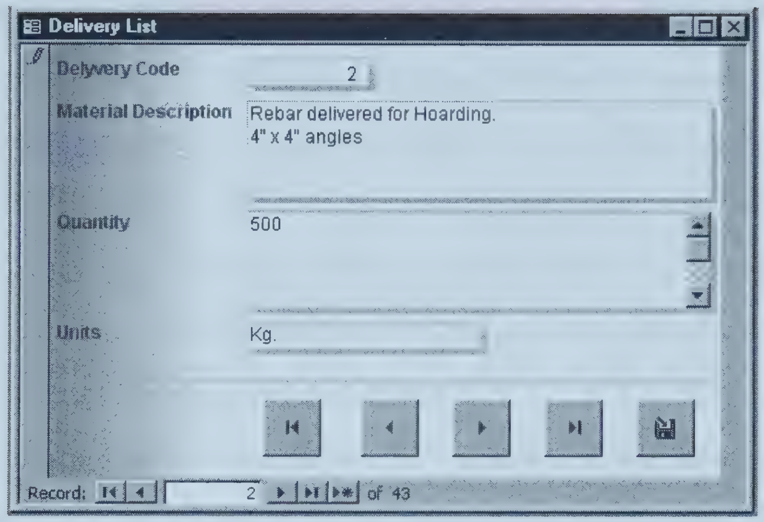


Figure 4.13 Delivery List

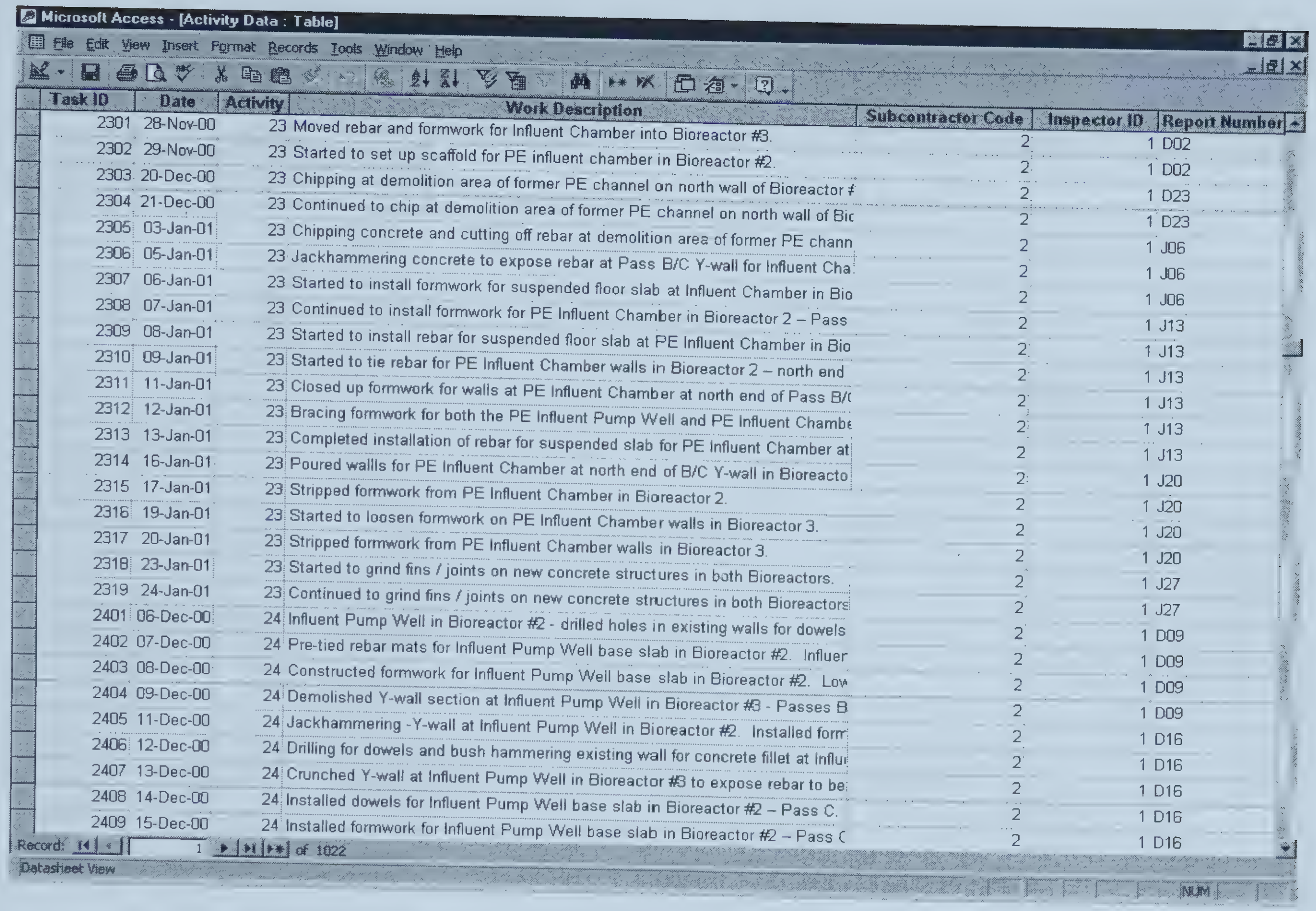
A total of 175 daily site reports were analyzed and transferred into the as-built database. A total of 1022 individual tasks were performed on 75 activities, for the case study project. An as-built report containing all the information stored into the database is obtained by selecting the as-built report option in the main window in Figure 4.7. This report is organized by Activity ID numbers, and for each activity the individual tasks that comprise the activity are organized by starting date of each task. Appendix F contains the as-built report produced for the case study project.

4.4.5 Extraction of the As-built Schedule from the Database

After the transfer of information from the daily inspector site reports into the database, the next step is to extract an as-built schedule from the as-built database. The starting point of this process begins with the Task Data table produced in the previous section. Figure 4.14 shows a segment of the Task Data table, where the information it

contains is displayed in table form. Figure 4.14 shows the individual tasks that comprise two activities, activity No. 23, "Construction of Concrete Influent Chamber", and activity No. 24, "Construction of Concrete Influent Pump Well" (refer to the third column in Figure 4.14). Figure 4.14 also shows all the tasks that comprise each activity, organized by start date. Refering to the first two columns of Figure 4.14, the first task of activity No. 23 (task no. 2301), was performed on November 28, 2000, and the last task of activity No. 23 (task no. 2319) was performed on January 24, 2001.

The data in the Task Data table are then imported into the Primavera Project Planner (P3) program. The schedule is then processed using P3. As can be seen in Figure 4.14, the Task Data table contains one record for each daily task performed. When this information is imported into P3, the program generates a one-day activity duration for each task performed. Figure 4.15 graphically portrays the data contained in the Task Data table segment shown in Figure 4.14. Figure 4.15 shows that the duration of each task is one day and that an activity is comprised by several one-day duration activities. An associated Work Breakdown Structure was created in the P3 file that contains each activity ID and makes it possible to summarize all of the one-day duration activities that belong to each activity. The subtotal rows in Figure 4.15, show the summary bars that depicts the as-built duration of activities No. 23 and No. 24. The wide portions of the summary bars represent daily periods were work was reported in the daily inspector site reports, the narrow sections of the summary bars represent days when work was not performed.



Microsoft Access - [Activity Data : Table]

Task ID	Date	Activity	Work Description	Subcontractor Code	Inspector ID	Report Number
2301	28-Nov-00	23	Moved rebar and formwork for Influent Chamber into Bioreactor #3.	2	1	D02
2302	29-Nov-00	23	Started to set up scaffold for PE influent chamber in Bioreactor #2.	2	1	D02
2303	20-Dec-00	23	Chipping at demolition area of former PE channel on north wall of Bioreactor #	2	1	D23
2304	21-Dec-00	23	Continued to chip at demolition area of former PE channel on north wall of Bic	2	1	D23
2305	03-Jan-01	23	Chipping concrete and cutting off rebar at demolition area of former PE chann	2	1	J06
2306	05-Jan-01	23	Jackhammering concrete to expose rebar at Pass B/C Y-wall for Influent Cha	2	1	J06
2307	06-Jan-01	23	Started to install formwork for suspended floor slab at Influent Chamber in Bio	2	1	J06
2308	07-Jan-01	23	Continued to install formwork for PE Influent Chamber in Bioreactor 2 – Pass	2	1	J13
2309	08-Jan-01	23	Started to install rebar for suspended floor slab at PE Influent Chamber in Bio	2	1	J13
2310	09-Jan-01	23	Started to tie rebar for PE Influent Chamber walls in Bioreactor 2 – north end	2	1	J13
2311	11-Jan-01	23	Closed up formwork for walls at PE Influent Chamber at north end of Pass B/(	2	1	J13
2312	12-Jan-01	23	Bracing formwork for both the PE Influent Pump Well and PE Influent Chambe	2	1	J13
2313	13-Jan-01	23	Completed installation of rebar for suspended slab for PE Influent Chamber at	2	1	J13
2314	16-Jan-01	23	Poured wallls for PE Influent Chamber at north end of B/C Y-wall in Bioreacto	2	1	J20
2315	17-Jan-01	23	Stripped formwork from PE Influent Chamber in Bioreactor 2.	2	1	J20
2316	19-Jan-01	23	Started to loosen formwork on PE Influent Chamber walls in Bioreactor 3.	2	1	J20
2317	20-Jan-01	23	Stripped formwork from PE Influent Chamber walls in Bioreactor 3.	2	1	J20
2318	23-Jan-01	23	Started to grind fins / joints on new concrete structures in both Bioreactors.	2	1	J27
2319	24-Jan-01	23	Continued to grind fins / joints on new concrete structures in both Bioreactors	2	1	J27
2401	06-Dec-00	24	Influent Pump Well in Bioreactor #2 - drilled holes in existing walls for dowels	2	1	D09
2402	07-Dec-00	24	Pre-tied rebar mats for Influent Pump Well base slab in Bioreactor #2. Influer	2	1	D09
2403	08-Dec-00	24	Constructed formwork for Influent Pump Well base slab in Bioreactor #2. Low	2	1	D09
2404	09-Dec-00	24	Demolished Y-wall section at Influent Pump Well in Bioreactor #3 - Passes B	2	1	D09
2405	11-Dec-00	24	Jackhammering -Y-wall at Influent Pump Well in Bioreactor #2. Installed forr	2	1	D16
2406	12-Dec-00	24	Drilling for dowels and bush hammering existing wall for concrete fillet at Influ	2	1	D16
2407	13-Dec-00	24	Crunched Y-wall at Influent Pump Well in Bioreactor #3 to expose rebar to be	2	1	D16
2408	14-Dec-00	24	Installed dowels for Influent Pump Well base slab in Bioreactor #2 – Pass C.	2	1	D16
2409	15-Dec-00	24	Installed formwork for Influent Pump Well base slab in Bioreactor #2 – Pass (	2	1	D16

Record: 1 of 1022

Datasheet View

Figure 4.14 Segment of the Task Data Table

Figure 4.15 Time-scaled Illustration of the Task Data Table from Primavera Project Planner

If no work is noted for an activity during a specific day, this may not always mean that no work was performed. Gaps within groups of activities were evaluated to determine if work on the activity was postponed or if it was simply a case that no work has been recorded in the inspector daily site reports, altough the activity was on-going. In order to do this, a relationship threshold was established: i.e., a number of days of idleness inside a group of individual task belonging to the same activity, which could logically define a split within an activity. Most of the activities in the case study project have average durations of aproximately three weeks; in this case, a relationship threshold of 5 days was established. A smaller relationship threshold was established in the case of activities having smaller durations. If a group of records was separated by less than the relationship threshold, the two points in time representing the first and last recorded days of work were connected with a solid line representing continuous work on an activity. In Figure 4.15, it is evident that large gaps indicate that work on an activity was interrupted, and the narrow line connecting the two activity portions represents the split. This process of determining the as-built activity durations was applied to every activity on the schedule and the final result can be observed in Figure 5.33 on Chapter 5.

Logical relationships between task groups or activities were inferred by observing activity finish dates that are consecutive with logically dependent start dates. For each activity, possible successors were identified by determining if their start dates were within the relationship threshold of the predecessor's finish date. In this case a relationship threshold of three days was established as the maximum amount of time between the finish date of an activity and the start date of its successor. In the case of activities with no apparent successors, start constraints were established. Once the as-built schedule logic had been inferred and derived, CPM calculations were performed and critical paths

were determined. The information contained in the as-built schedule was then compared and reconciled with the project as-planned schedule. Appendix G contains the case study as-built schedule obtain after transferring each record of information in the Task Data Table into the P3 file.

4.4.6 Quantifying the Delays

After creating the as-built schedule, the next step was to identify the significant problems, which exercised control over the project and thus generated delays. The procedure to determine delays focused on comparing as-planned and as-built project schedules. The comparison between the as-planned and as-built schedules was performed to identify and quantify project delays and to provide a basis to show the reasons why major milestones could not be achieved because of unavoidable issues.

In order to correctly analyze the delays, each activity was assesed separately. Whenever a delay was recognized in an activity, a careful review of the information contained in the as-built database was performed to find out what factors influenced the normal progress of the specific activity. This analysis was performed to reach conclusions about the causes, type and magnitude of the delays.

These delays included either variances in the duration of an activity or extended duration (delay Type 3, explained in Section 3.4.2); or a delay in the start of an activity due to variances between the as-planned and as-built finish-to-start or start-to-start lag durations (delays Type 1 and 2, explained in Section 3.4.2).

Delays in extended activity durations were quantified by comparing the as-planned duration to the as-built duration, and calculating the variances in activity

durations. These variances could be either positive in the case of schedule delays, or negative in the case of accelerated performance.

Delays in the early start of an activity were determined by comparing the as-planned lag duration to the as-built lag duration of an activity in relationship to its logical predecessor and successor activities. Two types of predecessor and successor relationships were used in the project as-planned and as-built schedules. These included finish-to-start relationships and start-to-start relationships. Again, these variances could be either positive or negative, where positive variances represent delays and negative variances represent accelerated performance.

Finally, interviews with project management were conducted to review and verify the findings of the analysis, which addresses significant issues that impacted project activities.

4.5 Summary

The as-planned schedule depicts the contractor's planned construction sequences prior to the occurrence of any project delays. Several as-planned schedules were reviewed prior to selecting the most appropriate as-planned data source for this analysis. The objective behind these reviews was to determine the activity durations and work sequences, based upon physical constraints and normal construction sequences.

Once the as-planned schedule was established, the next step was to prepare an as-built database and to derive an as-built schedule from the database. The creation of an as-built database included the design of the database structure based on the information contained in the inspector's daily site reports, the transfer of information from daily site reports into the appropiate database windows and specific fields of information,

and the extraction of the as-built schedule from the database by importing the information contained in the Task Data table into Primavera Project Planner (P3). The P3 file graphically portrays the data contained in the database. The time-scalled illustration created in the P3 file is interpreted to determine as-built activity durations.

The dates used for the as-built schedule were recorded from different contemporaneous project documentation, mainly the inspector's daily site reports. The as-built schedule is comprised of the same activities found in the as-planned schedule, with the inclusion of the necessary activities that were actually performed and that made up part of the project work scope. To the greatest extent possible, every effort was made to define the as-built activities in a manner consistent with the original scope contemplated in the contractor's as-planned schedule.

The comparison between the as-planned and as-built schedules was useful to determine deviations from the as-planned schedule and to identify problems and delays that affected the actual sequence of construction. Whenever it was determined that an activity was delayed, a complete review of the information contained in the as-built database was performed to draw correct conclusions with respect to the delay and its causes.

CHAPTER 5 ANALYSIS OF CASE STUDY: BIOREACTORS UPGRADE

5.1 Introduction

The effectiveness of the fuzzy logic model explained in Chapter 3 was validated using the case study information of the project described in Chapter 4. This project consisted of retrofitting existing Bioreactors and Secondary Clarifiers of a local wastewater treatment plant. The as-planned schedule was the starting point and it was sequentially updated each time a delay occurred on a project activity. As the project gradually progressed, different snapshots were taken during its project life. Figure 5.1 shows the as-planned bar chart schedule of the project. Figure 5.2 shows the as-planned schedule translated into a network diagram. Figures 5.1 and 5.2 show that the work was scheduled to start on October 10, 2000, and to be completed on February 18, 2001.

There are two critical paths on this project. The first critical path includes activities 01, "Mobilization"; 02, "Protection of Exterior Tanks"; 04, "Mechanical Removals - 100 mm Proces Air (PRA) coarse bubble aeration"; 05, "Mechanical Removals - Process Air Headers (400 mm Proces Air (PRA))"; 32, "Mixed Liquor (ML) piping delivery"; 33, 'Mixed Liquor (ML) piping install"; 15, "Construction of concrete Influent Pump Well"; 20, "Construction of Concrete baffle walls"; 16, "Concrete pipe supports".

The second critical path includes activities 01, "Mobilization"; 02, "Protection of Exterior Tanks"; 07, "Secondary Clarifier Concrete Demolition"; 08, "Bioreactor Concrete Demolition"; 15, "Construction of concrete Influent Pump Well"; 20, "Construction of Concrete baffle walls"; 16, "Concrete pipe supports".

The facts relevant to project delays that occurred are given in Figure 5.3. This information was constructed based on the information contained in the as-built database prepared for this project. Figure 5.4 shows the cause/effect matrix used to categorize the delays.

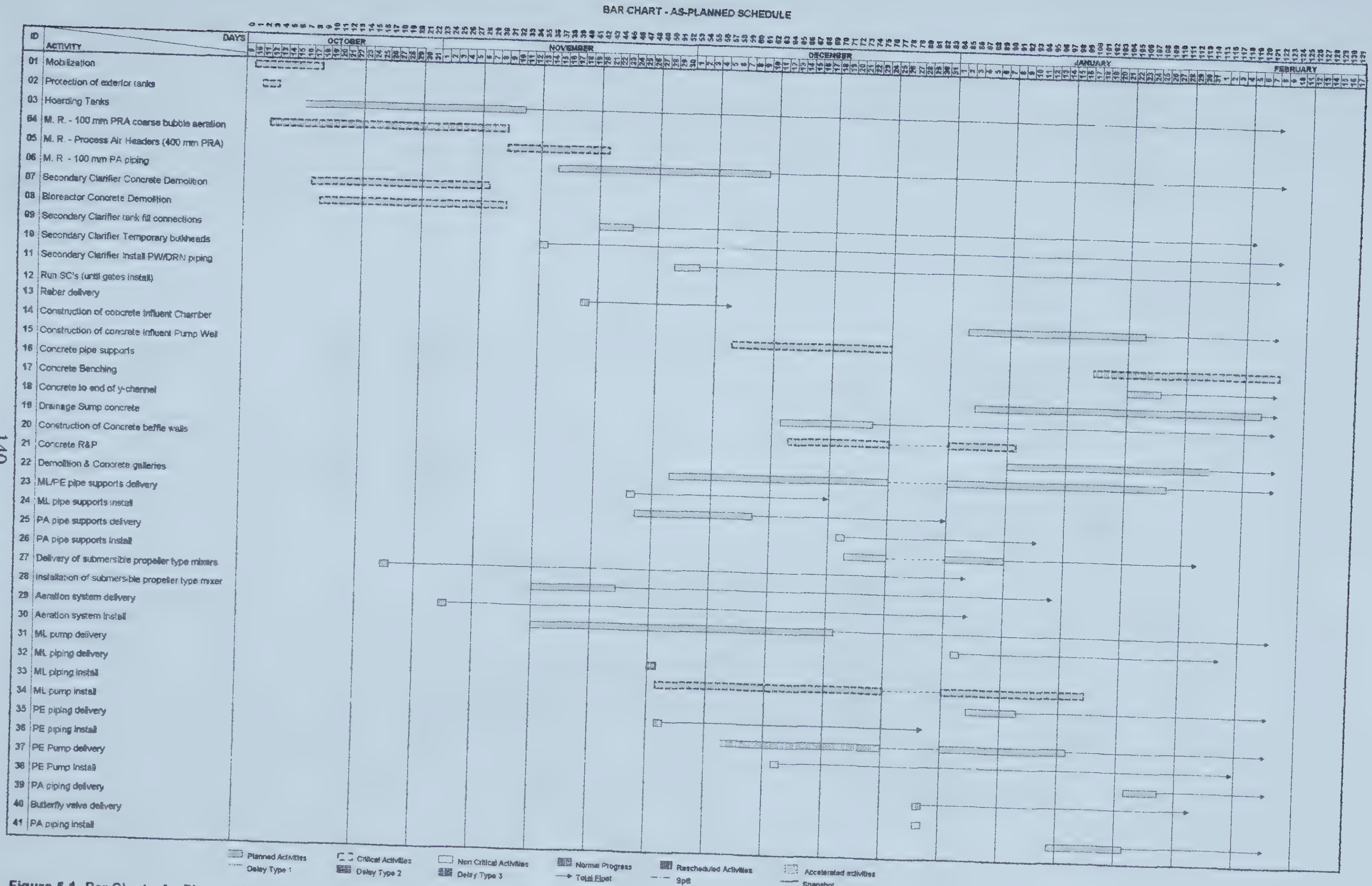


Figure 5.1 Bar Chart - As-Planned Schedule for Case Study

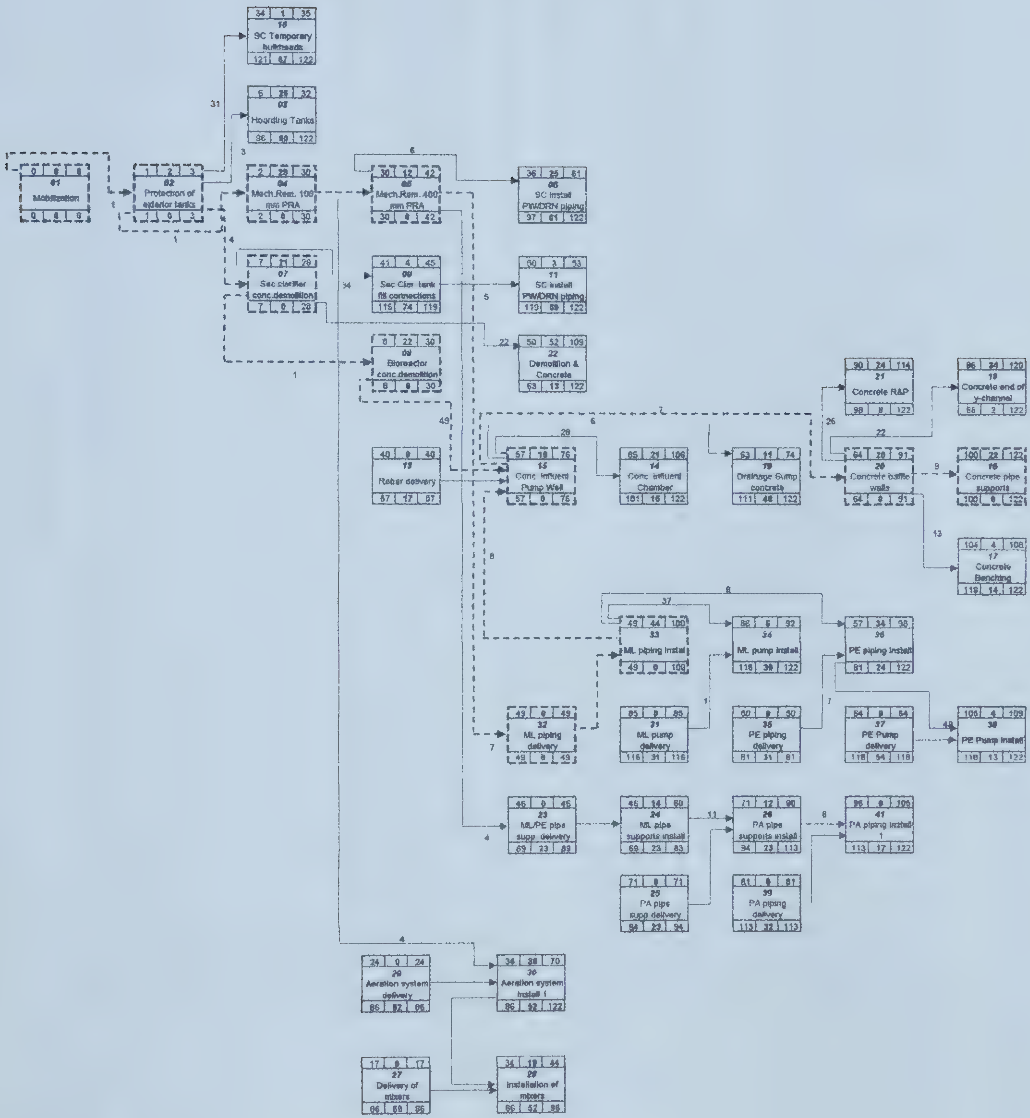


Figure 5.2 Network Diagram - As-Planned Schedule for Case Study

ID	Activity	Original Duration Days	Type of Delay	Description of Delays
3	Hoarding Tanks	26	Type 3	Unable to complete installation of hoarding over tanks due to wind. Installation hampered by windy conditions.
			Type 3	Subcontractor #1 has no control over their concrete subcontractor (Subcontractor #2). Subcontractor #1 continuously after Subcontractor #2 to close up hoarding (lowering / removing equipment, debris, chipping of walls, etc). As fast as Subcontractor #1 installs and closes up, Subcontractor #2 opens it up and leaves it open.
4	M. R. - 100 mm PRA coarse bubble aeration diffusers	28	Type 3	Issued Change Notice (Removal of abandoned piping at north end of Primary Effluent Y-wall channel).
5	M. R. - Process Air Headers	12	Type 1	Started delay due to preceding delay to M.R. - 100 mm PRA coarse bubble aeration diffusers. Completed within duration originally planned.
7	Sec. Clarifier Conc. Demolition	21	Type 3	Extending the slide plate openings from the ML channel into the Clarifiers has been very time consuming and expensive. Concrete cutting and coring slow in Clarifiers 2 & 3. Limited access space has impacted progress in coring of concrete mixed liquor distribution channel at front end of Clarifiers 2 & 3. Removal of concrete debris is totally manual labour: buckets, ropes, wheel barrels, etc.
8	Bioreactor Concrete Demolition	22	Type 3	Demolition of Y-wall using the Brokk BM250 ram jackhammer machine is extremely slow and expensive. Both Subcontractor #1 & Inspector had questioned using a Bobcat instead of wheelbarrows when Subcontractor #2 was moving debris in Bioreactor #2.
			Type 3	Re-coring holes at corners for drainage sump in Bioreactor #3 – Pass C – cored in wrong place (had to remove diffuser piping already installed).
			Type 3	Work limited in Bioreactors today due to flooding. Liquid backing up into Bioreactors through under tank drainage system due to pump tripping out in wet well west of Bioreactor #1. General clean up to get rid of pooled liquid. Inspector Sent e-mail to Owner on above – verbal response from Owner is that contractor is responsible to prevent any flooding in tanks.
14	Construction of concrete Influent Chamber	21	Type 2	Started delay due to discrepancy in dimensions between Demolition, Structural and Process drawings for PE influent chamber at north end of Y-wall.
15	Construction of concrete Influent Pump Well	19	Type 2	Started delay due discrepancy in Influent Pump Well dimensions. Questioned Consultant/Designer on missing details, discrepancy in drawings, potential interference with removal of pumps, etc.
			Type 3	Worked on cleaning up deficiencies noted during inspection. Subcontractor #2 is all over the place, never seems to clean up any of the work before wandering off to another area. Superintendent is on and off site and never can be found when Subcontractor #1 wants to discuss progress.
16	Concrete pipe supports	22	Type 1	Started delay due to preceding delay to Construction of Concrete baffle walls. Completed within duration originally planned.
20	Construction of Concrete baffle walls	20	Type 2	Started delay due to lack of details on drawings for doors required. Consultant/Designer confirmed that the reference details are reversed and that a door is required only on south baffle wall – detail is missing.
21	Concrete R&P	24	Type 3	Concrete patching at demolition areas in Bioreactor 2 is falling off and ends of rebar are not protected properly.
23	ML/PE pipe supports delivery	0	Type 2	Started delay because S.S. pipe supports were incorrectly fabricated and all supports on site were being returned for modifications to suit fillet at bottom of Y-walls. Noted that not all pipe supports required modification as some are installed on the north wall of the Bioreactors.
24	ML pipe supports install	14	Type 1	Started delay due to preceding delay to ML/PE pipe supports delivery. Completed within duration originally planned.
30	Aeration system install	36	Type 3	Noted that diffuser holders were not being cleaned prior to assembling support plate, diffuser and ring – brought to attention of Subcontractor #1 superintendent. Diffusers were removed in Bioreactor 3 – Pass C (Cells 5 and 6) and diffuser holders were wiped clean then reassembled.
34	ML pump install	6	Type 3	Subcontractor #1 tried operation of davits for ML Recycle pumps – neither work in location installed – unable to remove pump from Bioreactors.

Figure 5.3 Delays Occurring on the Case Study Project

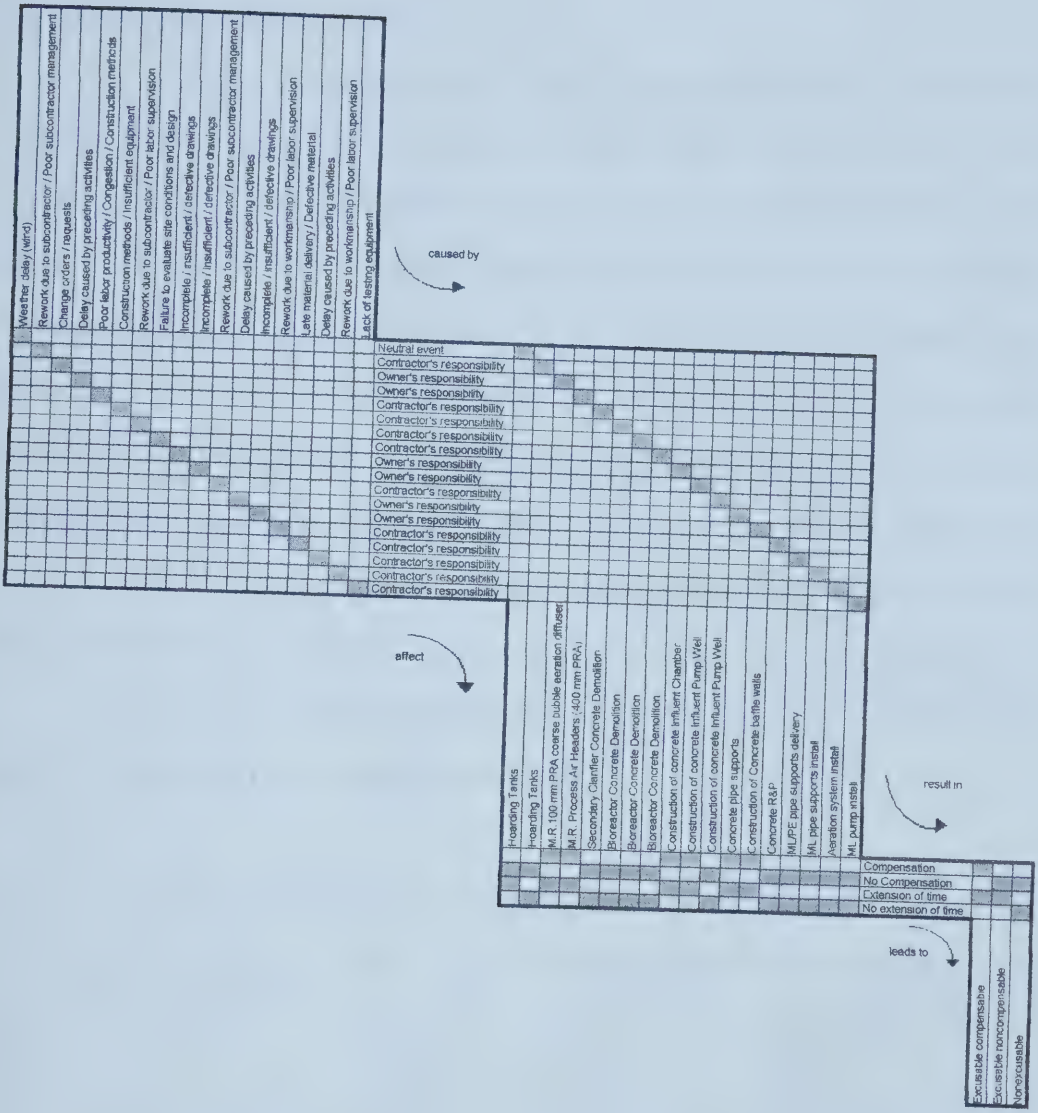


Figure 5.4 Delay Categorization Matrix for Case Study

5.2 Estimation of Delay Impacts

The procedure to estimate delay impacts was implemented in the form of a computer program in order to determine the duration of the delays presented in Figure 5.3. The delays affected the following activities: 03, "Hoarding Tanks"; 04, "Mechanical Removals - 100 mm Proces Air (PRA) coarse bubble aeration diffusers"; 05, "Mechanical Removals. - Process Air Headers (400 mm Proces Air (PRA)); 07, "Sec. Clarifier Conc. Demolition"; 08, "Bioreactor Concrete Demolition"; 14, "Construction of concrete Influent Chamber"; 15, "Construction of concrete Influent Pump Well"; 16, Concrete pipe supports"; 20, "Construction of Concrete baffle walls"; 21, "Concrete Repair & Patch"; 23, "Mixed Liquor (ML) / Primary Effluent (PE) pipe supports delivery"; 24, "Mixed Liquor (ML) pipe supports install"; 30, "Aeration system install"; 34, "Mixed Liquor (ML) pump install".

Tables 5.1 to 5.15 show the delay-sensitive attributes used to determine the duration of the delays that affected these activities.

Table 5.1 Delay-Sensitive Attributes for Hoarding Tanks (Delay 1)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Small Medium Small	Very Small Medium Very Large
Wind	High Average Low	Large Medium Small	Very Large Large Small
Location of the activity	Good Average Poor	Large Medium Small	Very Large Large Very Small

Table 5.2 Delay-Sensitive Attributes for Hoarding Tanks (Delay 2)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Large Medium Small	Very Large Large Very Large
Requires inspection	High Average Low	Large Medium Small	Very Large Large Very Small

Table 5.3 Delay-Sensitive Attributes for M. R. - 100 mm PRA coarse bubble aeration

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Small Small Small	Very Small Medium Very Large
Requires design changes / additions	High Average Low	Small Medium Small	Small Large Very Small

Table 5.4 Delay-Sensitive Attributes for Sec. Clarifier Conc. Demolition

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Medium Large Small	Large Very Large Very Large
How labor intensive	High Average Low	Large Medium Small	Very Large Large Very Small
Site congestion	High Average Low	Large Medium Small	Very Large Large Very Small

Table 5.5 Delay-Sensitive Attributes for Bioreactor Concrete Demolition (Delay 1)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Large Medium Small	Very Large Large Very Large
How equipment intensive	High Average Low	Large Medium Small	Very Large Large Very Small

Table 5.6 Delay-Sensitive Attributes for Bioreactor Concrete Demolition (Delay 2)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Medium Medium Small	Large Very Large Very Large
Requires inspection	High Average Low	Medium Small Small	Large Medium Very Small

Table 5.7 Delay-Sensitive Attributes for Bioreactor Concrete Demolition (Delay 3)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Small Medium Small	Very Small Large Very Large
Requires controlled environment	High Average Low	Medium Small Small	Large Small Very Small

Table 5.8 Delay-Sensitive Attributes for Construction of concrete Influent Chamber

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long	Medium	Large
	Medium	Medium	Very Large
	Short	Small	Very Large
Requires design changes / additions	High	Small	Medium
	Average	Medium	Large
	Low	Small	Very Small

Table 5.9 Delay-Sensitive Attributes for Construction of Conc. Infl. Pump Well (Delay 1)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long	Small	Small
	Medium	Small	Medium
	Short	Very Small	Medium
Requires design changes / additions	High	Small	Medium
	Average	Medium	Large
	Low	Small	Very Small

Table 5.10 Delay-Sensitive Attributes for Construction Conc. Infl. Pump Well (Delay 2)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long	Large	Very Large
	Medium	Medium	Large
	Short	Small	Very Large
Requires inspection	High	Large	Very Large
	Average	Medium	Large
	Low	Small	Very Small

Table 5.11 Delay-Sensitive Attributes for Construction of Concrete baffle walls

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Medium Small Small	Large Medium Very Large
Requires design changes / additions	High Average Low	Medium Small Small	Large Medium Very Small

Table 5.12 Delay-Sensitive Attributes for Concrete R&P

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Small Small Small	Very Small Medium Very Large
Requires inspection	High Average Low	Medium Small Small	Large Small Very Small

Table 5.13 Delay-Sensitive Attributes for ML/PE pipe supports delivery

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Medium Medium Small	Large Very Large Very Large
How material intensive	High Average Low	Medium Small Small	Large Medium Very Small

Table 5.14 Delay-Sensitive Attributes for Aeration system install

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Small Small Very Small	Very Small Medium Small
Requires inspection	High Average Low	Medium Medium Small	Large Very Large Very Small

Table 5.15 Delay-Sensitive Attributes for ML pump install

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Large Small Small	Very Large Medium Very Large
How equipment intensive	High Average Low	Large Medium Small	Very Large Large Very Small

The determination of delay durations was performed using the following translation of linguistic variables into fuzzy subsets. These values are the ones utilized by Smith and Hancher (1989) in their proposed methodology. This set of membership functions was utilized in this case study because it provides a better degree of overlap than those presented in Figure 3.5. (Refer to Section 3.5.2). Table 5.16 shows the membership function sets used to translate the linguistic variables describing the relation between frequency of occurrence and adverse consequences. Figure 5.5 is a graphical representation of the membership functions used. The following notation is used

throughout this thesis to denote membership functions. The fuzzy set "Large" can be defined as:

Large = [$x_1 = 0.6 \mid \mu_{Large}(x_1) = 0.5$, $x_2 = 0.7 \mid \mu_{Large}(x_2) = 0.9$, $x_3 = 0.8 \mid \mu_{Large}(x_3) = 0.9$, $x_4 = 0.9 \mid \mu_{Large}(x_3) = 0.5$]

In short, the fuzzy set "Large" can be expressed as:

Large = (0.6|0.5, 0.7|0.9, 0.8|0.9,0.9|0.5)

Table 5.16 Membership Functions to translate linguistic variables

Large	=	(0.6|0.5, 0.7|0.9, 0.8|0.9, 0.9|0.5)
Small	=	(0.1|0.5, 0.2|0.9, 0.3|0.9, 0.4|0.5)
Medium	=	(0.3|0.1, 0.4|0.7, 0.5|1.0, 0.6|0.7, 0.7|0.1)
Very Large	=	(0.8|0.1, 0.9|0.7, 1.0|1.0)
Very Small	=	(0.0|1.0, 0.1|0.7, 0.2|0.1)

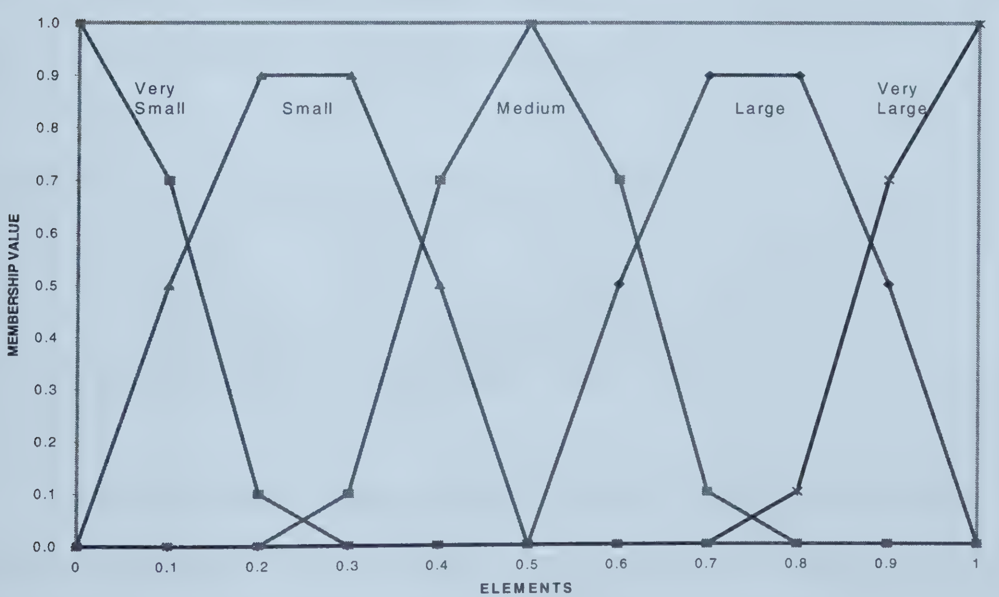


Figure 5.5 Membership functions for linguistic variables representing frequency of occurrence and adverse consequences. Smith and Hancher (1989).

Table 5.17 shows the membership function sets used to describe the delay duration in order to translate the linguistic variables describing the relation between adverse consequences and delay duration. These values are the ones utilized by Smith and Hancher (1989) in their proposed methodology. The variable z_i indicates an element of the delay duration. Whenever an activity is experiencing a delay, the user establishes his or her linguistic perception with respect to the delay duration, based on the magnitude or gravity of the adverse consequences on the delay duration. Based on his or her subjective judgment, the user establishes membership functions in order to express his or her belief of the delay duration that will experience that particular activity. For a particular activity the user determines the range of the delay duration. The extent of this range is determined its lower and uper limits, in this case z_1 and z_4. For instance, for the linguistic term "Very Large", the user may consider a delay duration of z_4 days as definitely being large, and a delay duration of z_1 days as definitely being small.

Table 5.17 Membership function sets to describe delay duration

Large	=	$(z_1 \| 0.0, z_2 \| 0.2, z_3 \| 0.9, z_4 \| 0.8)$
Small	=	$(z_1 \| 0.7, z_2 \| 0.9, z_3 \| 0.1, z_4 \| 0.0)$
Medium	=	$(z_1 \| 0.5, z_2 \| 0.9, z_3 \| 0.9, z_4 \| 0.5)$
Very Large	=	$(z_1 \| 0.0, z_2 \| 0.2, z_3 \| 0.8, z_4 \| 0.9)$
Very Small	=	$(z_1 \| 0.9, z_2 \| 0.7, z_3 \| 0.1, z_4 \| 0.0)$

The procedure to estimate delay impacts described in Section 3.5, was applied to all activities that suffered delays. Table 5.18 summarizes the mean delay durations and standard deviations obtained for each of the activities affected by delays.

Table 5.18 Delay Durations for Case Study

ID	Activity	Delay Duration Type 1		Delay Duration Type 2		Delay Duration Type 3		Interruption on Activity
		Mean	Variance	Mean	Variance	Mean	Variance	Crisp
3	Hoarding Tanks					3.18 18.133	0.78 1.89	15
4	M. R. - 100 mm PRA coarse bubble aeration diffusers					2.36	0.71	
5	M. R. - Process Air Headers (400 mm PRA)	2.36	0.71					
6	M. R. - 100 mm PA piping							70
7	Sec. Clarifier Conc. Demolition					18.36	1.54	
8	Bioreactor Concrete Demolition					41.556 5.04 4.18	2.20 0.81 0.78	13
14	Construction of concrete Influent Chamber			7.04	0.81			
15	Construction of concrete Influent Pump Well			3.19	0.79	22.354	1.53	13
16	Concrete pipe supports	5.18	0.77					4
20	Construction of Concrete baffle walls			5.18	0.77			4
21	Concrete Repair & Patch					3.40	0.69	
22	Demolition & Concrete galleries							6
23	ML/PE pipe supports delivery			4.40	0.66			
24	ML pipe supports install	4.40	0.66					
26	PA pipe supports install							6
28	Installation of submersible propeller type mixer							66
30	Aeration system install					3.36	0.68	
33	ML piping install							16
34	ML pump install					6.36	0.71	15
36	PE piping install							24

In the as-planned schedule (refer to Figure 5.1), interruptions to some of the activities were planned, because work was interrupted on site during the Christmas break (Week of December 25 to 31). During the course of the project, the extent of some of these interruptions was increased and additional activities were also interrupted. The occurrence of these interruptions was not related to any contemporaneous problem on site, rather they occurred due to the manner the contractor performed the work. For this reason the magnitude of these interruptions is crisp, since it is known or predicted with reasonable accuracy. The last column of Table 5.18 shows the total duration of the interruptions that the activities experienced.

5.3 Estimation of Triangular Membership Functions from Probability Density Functions

Table 5.18 shows the parameters of the PDF curves that represent delay durations. The fuzzy logic model transformed the values of the PDF curves, to obtain membership function curves, as described in Section 3.6. Figures 5.6 to 5.20 are a graphical representation of the fuzzy numbers estimated from the delay duration PDF's derived in the previous section.

Table 5.19 shows the PDF parameters for the delay durations obtained (mean and standard deviation) and also shows the corresponding triangular fuzzy numbers obtained after the transformations were performed.

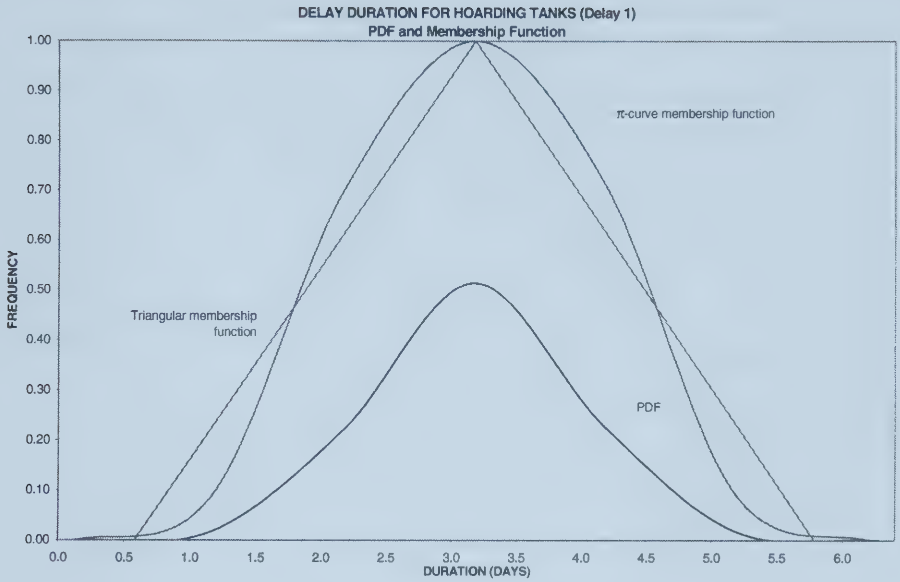


Figure 5.6 Delay duration for Hoarding Tanks (Delay 1)

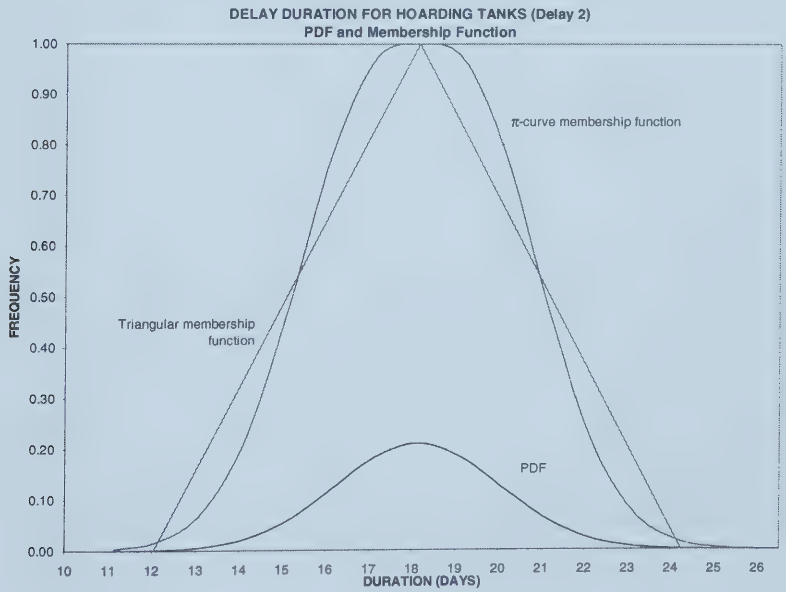


Figure 5.7 Delay duration for Hoarding Tanks (Delay 2)

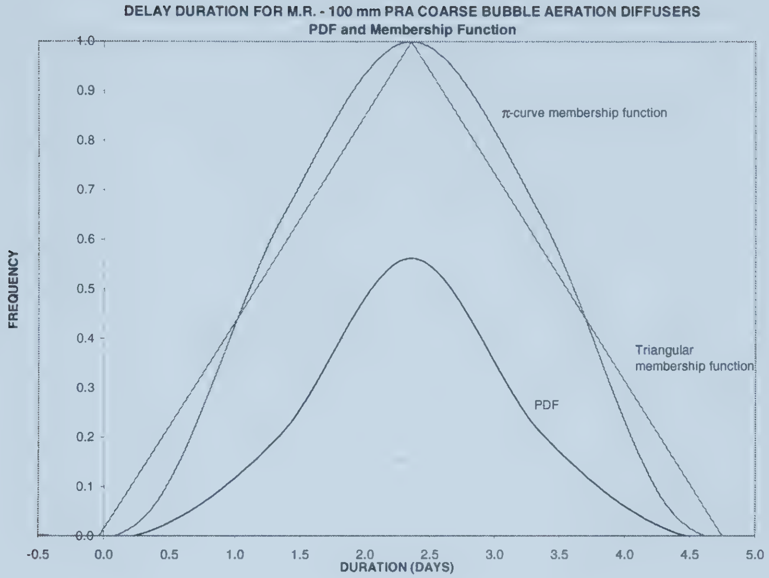


Figure 5.8 Delay duration for M.R. - 100 mm PRA coarse bubble aeration

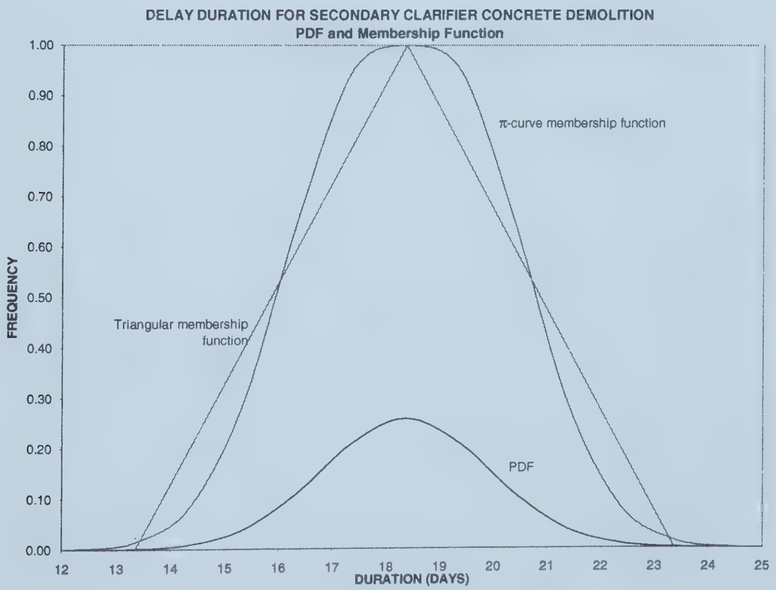


Figure 5.9 Delay duration for Secondary Clarifier Concrete Demolition

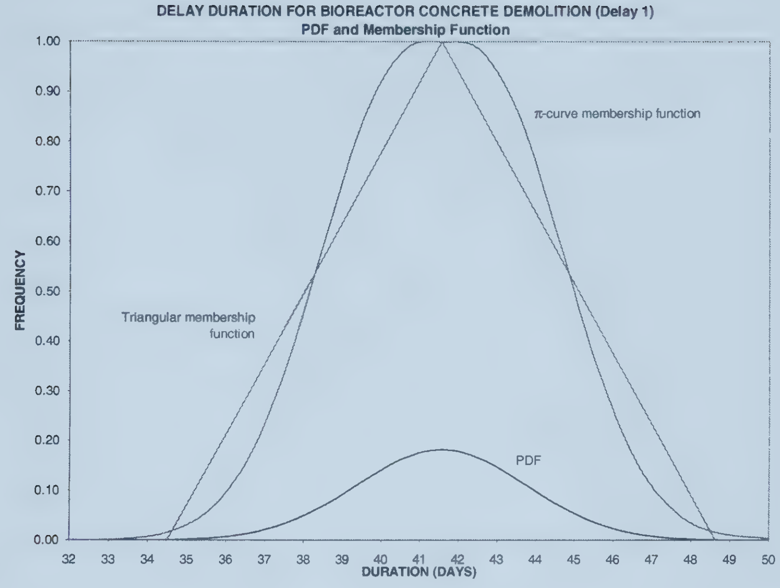


Figure 5.10 Delay duration for Bioreactor Concrete Demolition (Delay 1)

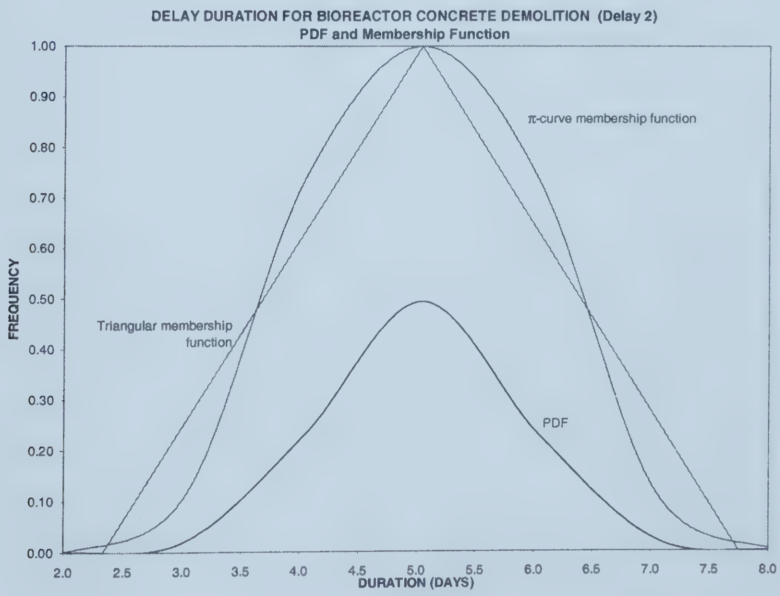


Figure 5.11 Delay duration for Bioreactor Concrete Demolition (Delay 2)

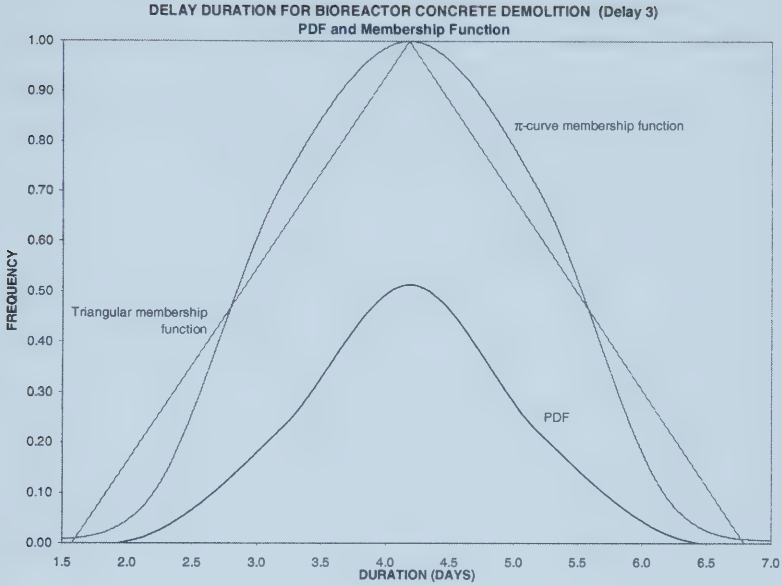


Figure 5.12 Delay duration for Bioreactor Concrete Demolition (Delay 3)

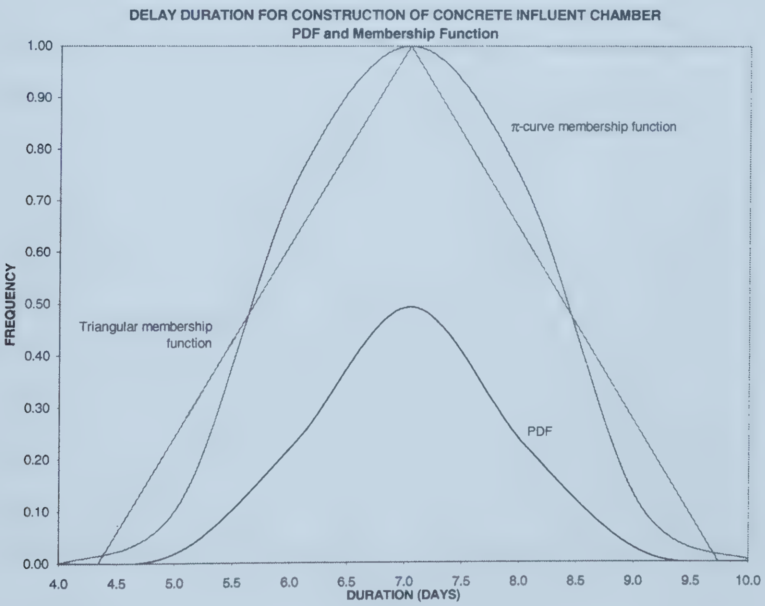


Figure 5.13 Delay duration for Construction of concrete Influent Chamber

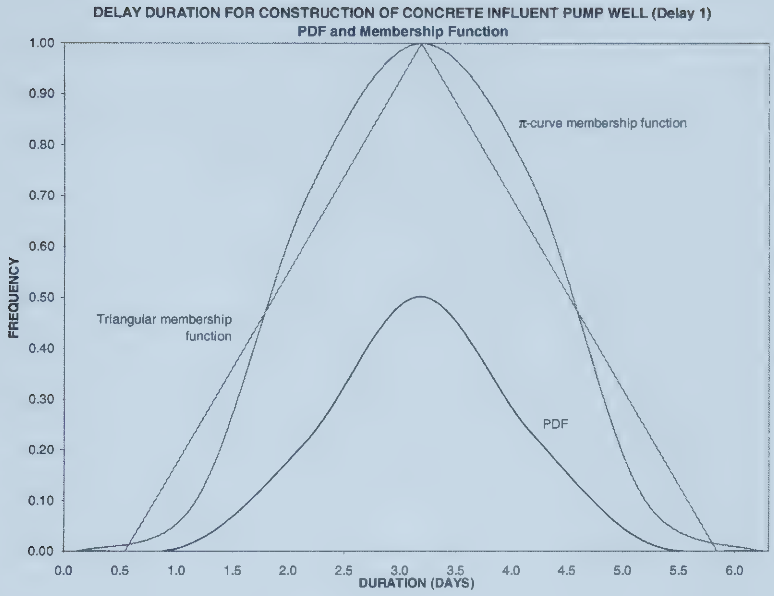


Figure 5.14 Delay duration for Construction of concrete Influent Pump Well (Delay 1)

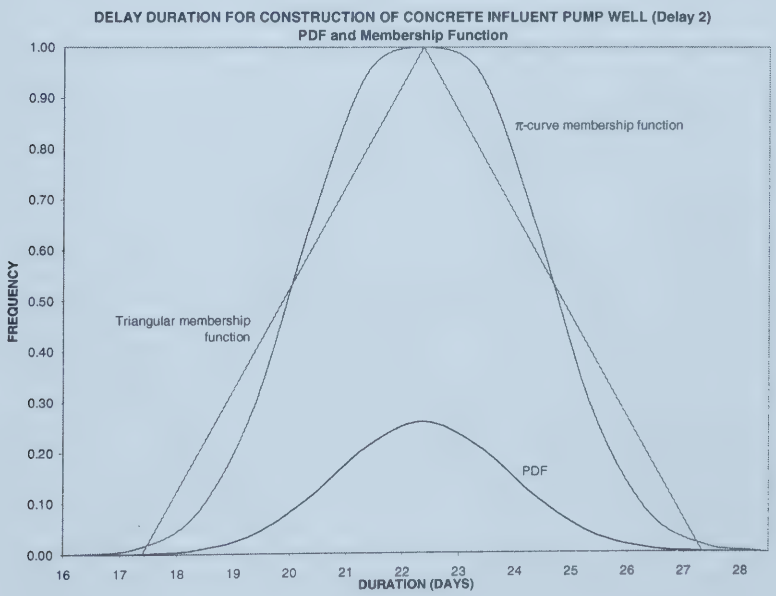


Figure 5.15 Delay duration for Construction of concrete Influent Pump Well (Delay 2)

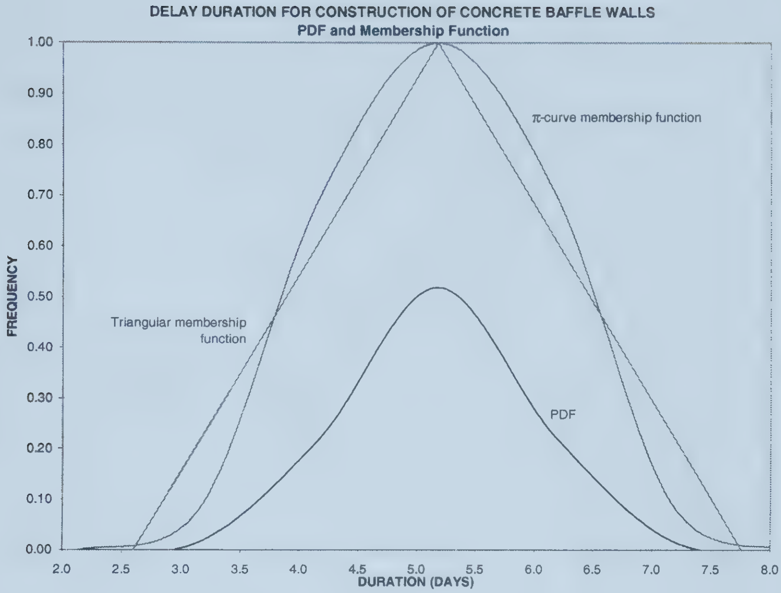


Figure 5.16 Delay duration for Construction of Concrete baffle walls

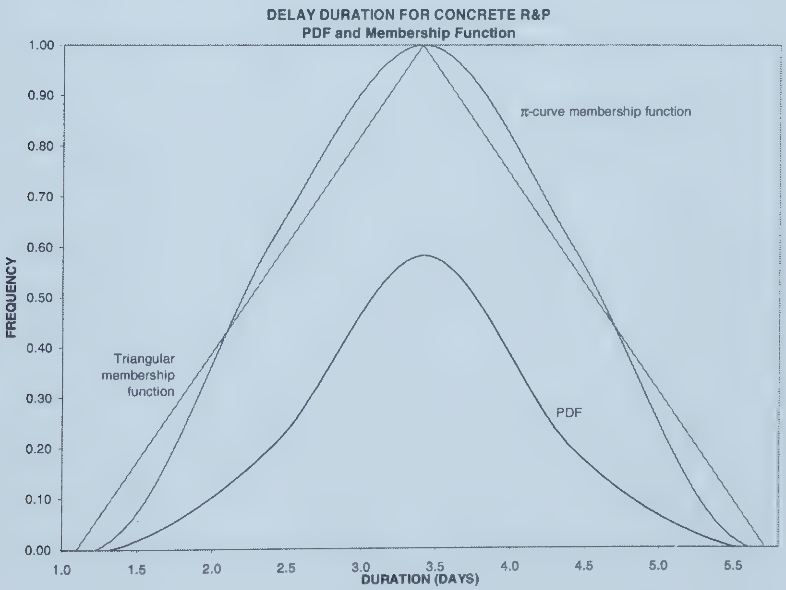


Figure 5.17 Delay duration for Concrete Repair & Patch

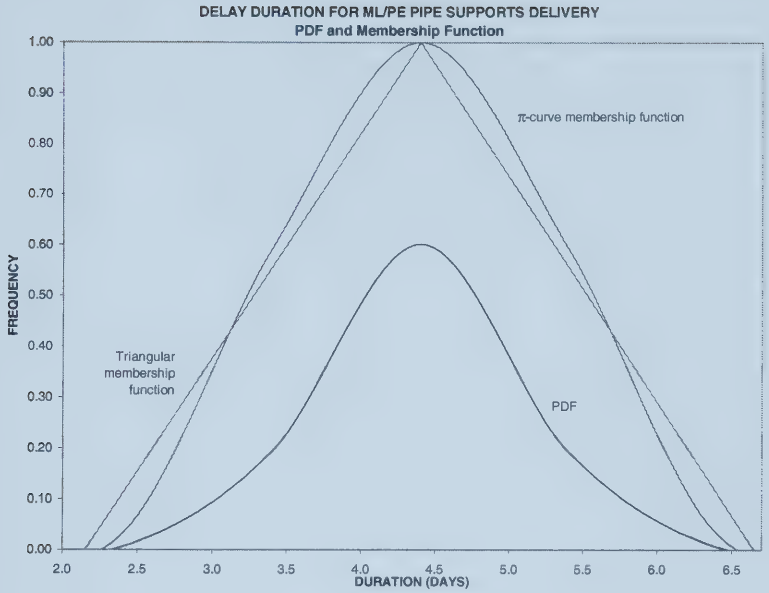


Figure 5.18 Delay duration for ML/PE pipe supports delivery

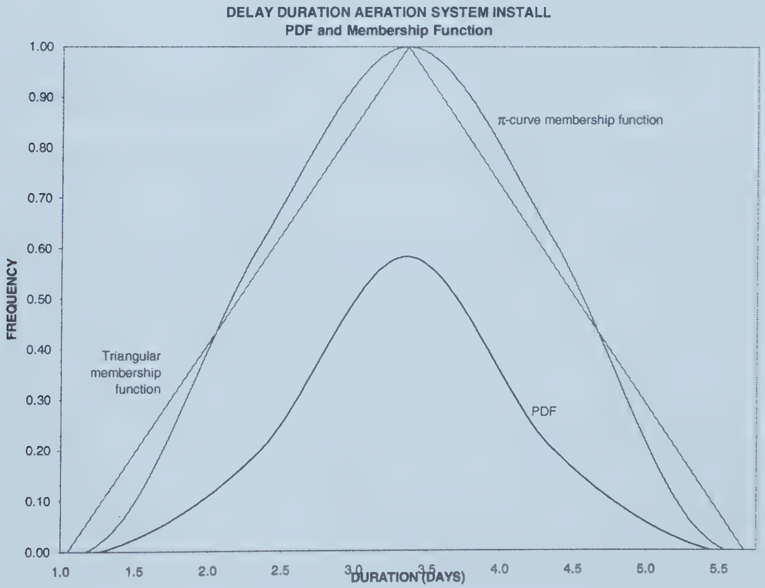


Figure 5.19 Delay duration for Aeration system install

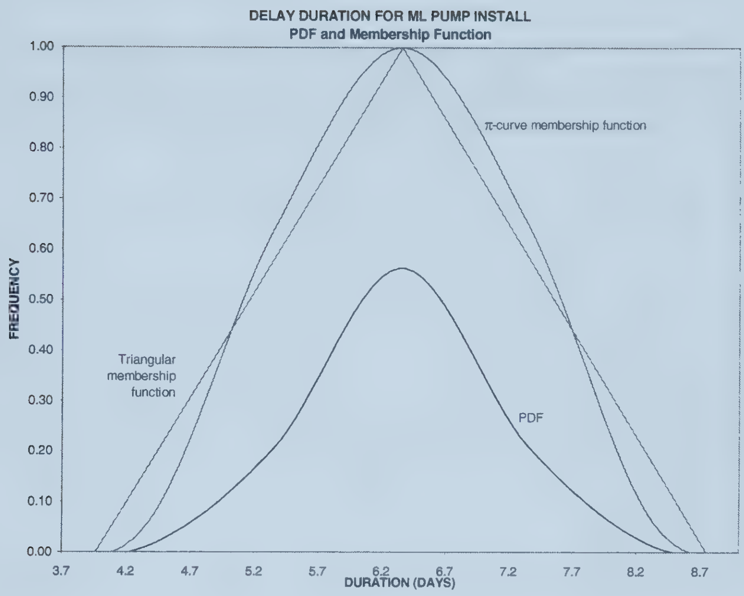


Figure 5.20 Delay duration for (Mixed Liquor) ML piping install

5.4 Revised Activity Durations

Table 5.20 shows all revised activity durations after they were increased by the amount of the delays they suffered using the procedure described in Section 3.7.

Table 5.19 Total Delay Durations for Case Study

ID	Activity	Delay Duration Type 1		Delay Duration Type 2		Delay Duration Type 3		Interruption on Activity	Triangular Fuzzy delay duration (Type 2 and 3)	Date of Occurrence
		Mean	Variance	Mean	Variance	Mean	Variance	Crisp		
3	Hoarding Tanks					3.18	0.78		(0.58 , 3.18 , 5.78)	27-Oct
						18.133	1.89		(12.03 , 18.13 , 24.24)	29-Nov
								15	(15.00 , 15.00 , 15.00)	14-Nov
4	M. R. - 100 mm PRA coarse bubble aeration diffusers					2.36	0.71		(-0.04 , 2.36 , 4.75)	20-Oct
5	M. R. - Process Air Headers (400 mm PRA)	2.36	0.71						(-0.04 , 2.36 , 4.75)	9-Nov
6	M. R. - 100 mm PA piping							70	(70.00 , 70.00 , 70.00)	18-Nov, 14-Dec
7	Sec. Clarifier Conc. Demolition					18.36	1.54		(13.35 , 18.36 , 23.37)	7-Nov
8	Bioreactor Concrete Demolition					41.556	2.20		(34.49 , 41.56 , 48.62)	18-Oct
						5.04	0.81		(2.33 , 5.04 , 7.75)	29-Nov
						4.18	0.78		(1.58 , 4.18 , 6.79)	4-Dec
								13	(13.00 , 13.00 , 13.00)	20-Dec
14	Construction of concrete Influent Chamber			7.04	0.81				(4.34 , 7.04 , 9.74)	3-Jan
15	Construction of concrete Influent Pump Well			3.19	0.79				(0.54 , 3.19 , 5.84)	6-Dec
						22.354	1.53		(17.38 , 22.35 , 27.33)	9-Dec
								13	(13.00 , 13.00 , 13.00)	22-Dec
16	Concrete pipe supports	5.18	0.77					4	(6.60 , 9.18 , 11.76)	18-Jan
20	Construction of Concrete baffle walls			5.18	0.77				(2.60 , 5.18 , 7.76)	13-Dec
								4	(4.00 , 4.00 , 4.00)	22-Dec
21	Concrete Repair & Patch					3.40	0.69		(1.10 , 3.40 , 5.71)	1-Feb
22	Demolition & Concrete galleries							6	(6.00 , 6.00 , 6.00)	22-Dec
23	ML/PE pipe supports delivery			4.40	0.66				(2.15 , 4.40 , 6.65)	24-Nov
24	ML pipe supports install	4.40	0.66						(2.15 , 4.40 , 6.65)	25-Nov
26	PA pipe supports install							6	(6.00 , 6.00 , 6.00)	21-Dec
28	Installation of submersible propeller type mixer							66	(66.00 , 66.00 , 66.00)	18-Nov, 19-Jan
30	Aeration system install					3.36	0.68		(1.05 , 3.36 , 5.67)	27-Nov
33	ML piping install							16	(16.00 , 16.00 , 16.00)	22-Dec, 13-Jan
34	ML pump install					6.36	0.71		(3.96 , 6.36 , 8.75)	25-Jan
								15	(15.00 , 15.00 , 15.00)	8-Jan
36	PE piping install							24	(24.00 , 24.00 , 24.00)	19-Dec, 6-Jan

ID	Activity	Original duration days	Normal Progress	First delay duration	Second delay duration	Third delay duration	Remaining duration	As-Built Revised duration
3	Hoarding Tanks	26	(11.00 , 11.00 , 11.00)	(0.58 , 3.18 , 5.78)	(12.03 , 18.13 , 24.24)		(15.00 , 15.00 , 15.00)	(38.61 , 47.32 , 56.02)
4	M. R. - 100 mm PRA coarse bubble areation diffusers	28	(8.00 , 8.00 , 8.00)	(-0.04 , 2.36 , 4.75)			(20.00 , 20.00 , 20.00)	(27.96 , 30.36 , 32.75)
5	M. R. - Process Air Headers (400 mm PRA)	12	(12.00 , 12.00 , 12.00)	(-0.04 , 2.36 , 4.75)				(12.00 , 12.00 , 12.00)
6	M. R. - 100 mm PA piping	25	(25.00 , 25.00 , 25.00)					(25.00 , 25.00 , 25.00)
7	Sec. Clarifier Conc. Demolition	21	(21.00 , 21.00 , 21.00)	(13.35 , 18.36 , 23.37)				(34.35 , 39.36 , 44.37)
8	Bioreactor Concrete Demolition	22		(34.49 , 41.56 , 48.62)	(2.33 , 5.04 , 7.75)	(1.58 , 4.18 , 6.79)	(22.00 , 22.00 , 22.00)	(60.40 , 72.78 , 85.16)
14	Construction of concrete Influent Chamber	21		(4.34 , 7.04 , 9.74)			(21.00 , 21.00 , 21.00)	(25.34 , 28.04 , 30.74)
15	Construction of concrete Influent Pump Well	19		(0.54 , 3.19 , 5.84)	(17.38 , 22.35 , 27.33)		(19.00 , 19.00 , 19.00)	(36.92 , 44.54 , 52.17)
16	Concrete pipe supports	22	(22.00 , 22.00 , 22.00)	(6.60 , 9.18 , 11.76)				(22.00 , 22.00 , 22.00)
20	Construction of Concrete baffle walls	20		(2.60 , 5.18 , 7.76)			(20.00 , 20.00 , 20.00)	(22.60 , 25.18 , 27.76)
21	Concrete R&P	24	(24.00 , 24.00 , 24.00)	(1.10 , 3.40 , 5.71)				(25.10 , 27.40 , 29.71)
22	Demolition & Concrete galleries	52	(52.00 , 52.00 , 52.00)					(52.00 , 52.00 , 52.00)
23	ML/PE pipe supports delivery	0		(2.15 , 4.40 , 6.65)				(2.15 , 4.40 , 6.65)
24	ML pipe supports install	14	(14.00 , 14.00 , 14.00)	(2.15 , 4.40 , 6.65)				(14.00 , 14.00 , 14.00)
26	PA pipe supports install	12	(12.00 , 12.00 , 12.00)					(12.00 , 12.00 , 12.00)
28	Installation of submersible propeller type mixer	10	(10.00 , 10.00 , 10.00)					(10.00 , 10.00 , 10.00)
30	Aeration system install	36	(14.00 , 14.00 , 14.00)	(1.05 , 3.36 , 5.67)			(22.00 , 22.00 , 22.00)	(37.05 , 39.36 , 41.67)
33	ML piping install	44	(44.00 , 44.00 , 44.00)					(44.00 , 44.00 , 44.00)
34	ML pump install	6	(6.00 , 6.00 , 6.00)	(3.96 , 6.36 , 8.75)				(9.96 , 12.36 , 14.75)
36	PE piping install	34	(34.00 , 34.00 , 34.00)					(34.00 , 34.00 , 34.00)

Table 5.20 As-Built Revised Activity Durations

5.5 Results of the Case Study Analysis

The following sections analyze the calculations performed to update the schedule. Different snapshots were performed on the project based on the occurrences of delays. The effects that different delays caused on the schedule and their corresponding consequences are also analyzed in each snapshot.

5.5.1 Snapshot 1

Snapshot 1 was performed at the beginning of day 9, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 1 (Figure 5.21), a delay has arisen on activity No. 8, "Bioreactor Concrete Demolition". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.5. (Refer to Section 5.2) Figure 5.10 shows the delay duration PDF and membership function (refer (refer to Section 5.3).

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.22 incorporates actual durations. The activity experiencing a delay has been shaded. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.1. Figure 5.23 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 1 are included in Appendix H.

Activity No. 8, "Bioreactor Concrete Demolition", was critical on the as-planned schedule and remains critical on the actual schedule. The delay it suffered has no effect upon the completion of the works due to the fact that only its start time is critical to the project. The extension of its duration, and its finish times are not critical to the project completion time. Since the activity started as planned, its start times are known and are crisp. The relationship with its only successor, activity No. 15 "Concrete Influent Pump Well", is a start-to-start relationship. For this reason activity No. 15 also has crisp start times and is not affected by the delay on activity No. 8. The only fuzzy values on the snapshot 1 schedule are the duration and finish times of activity No. 8. The critical paths remain unchanged. The project completion time on the as-planned schedule was 122 days, and after 8 days of progress the actual project completion time has not been modified.

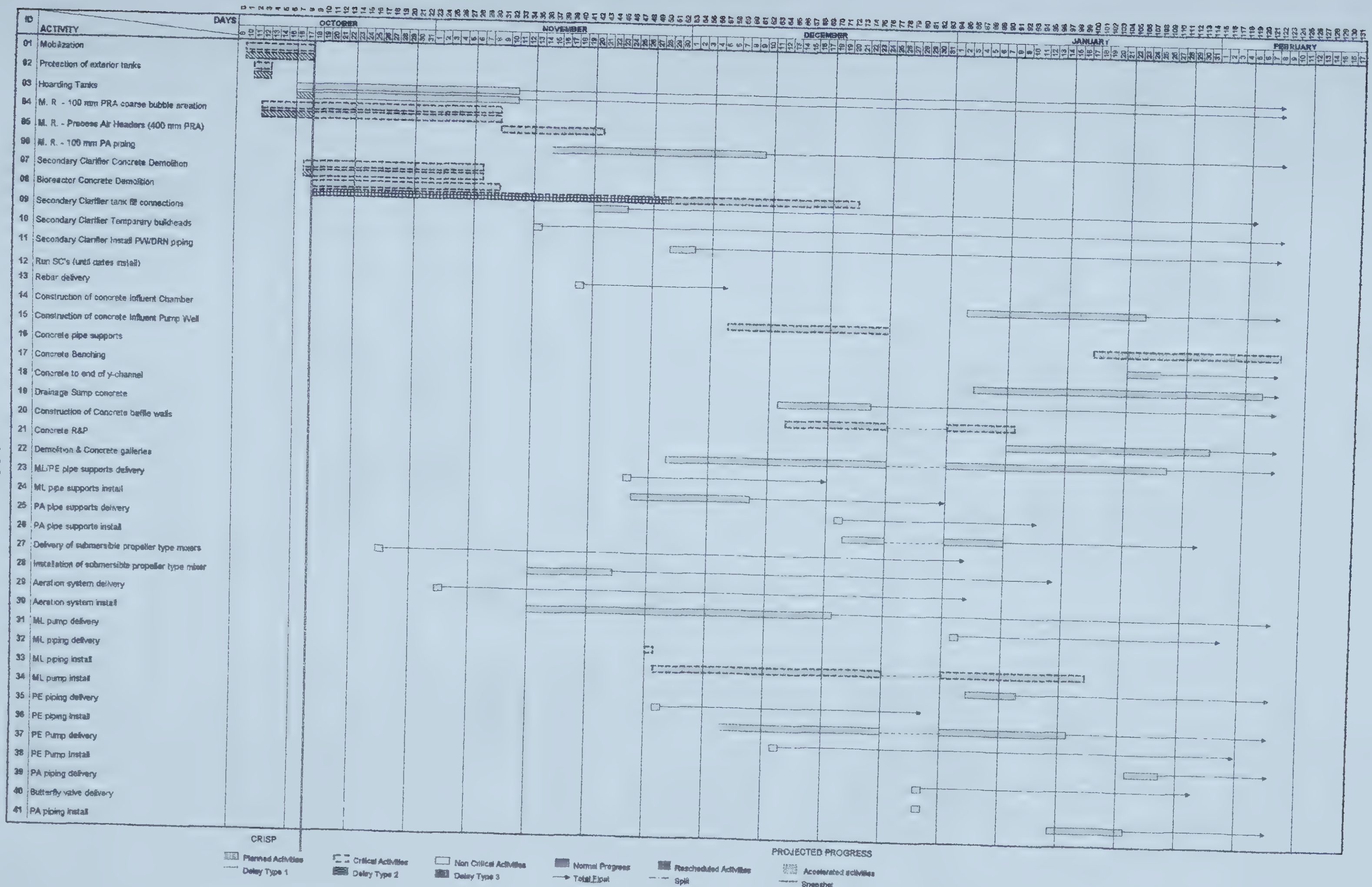


Figure 5.21 Bar Chart Schedule - Snapshot 1 of Case Study

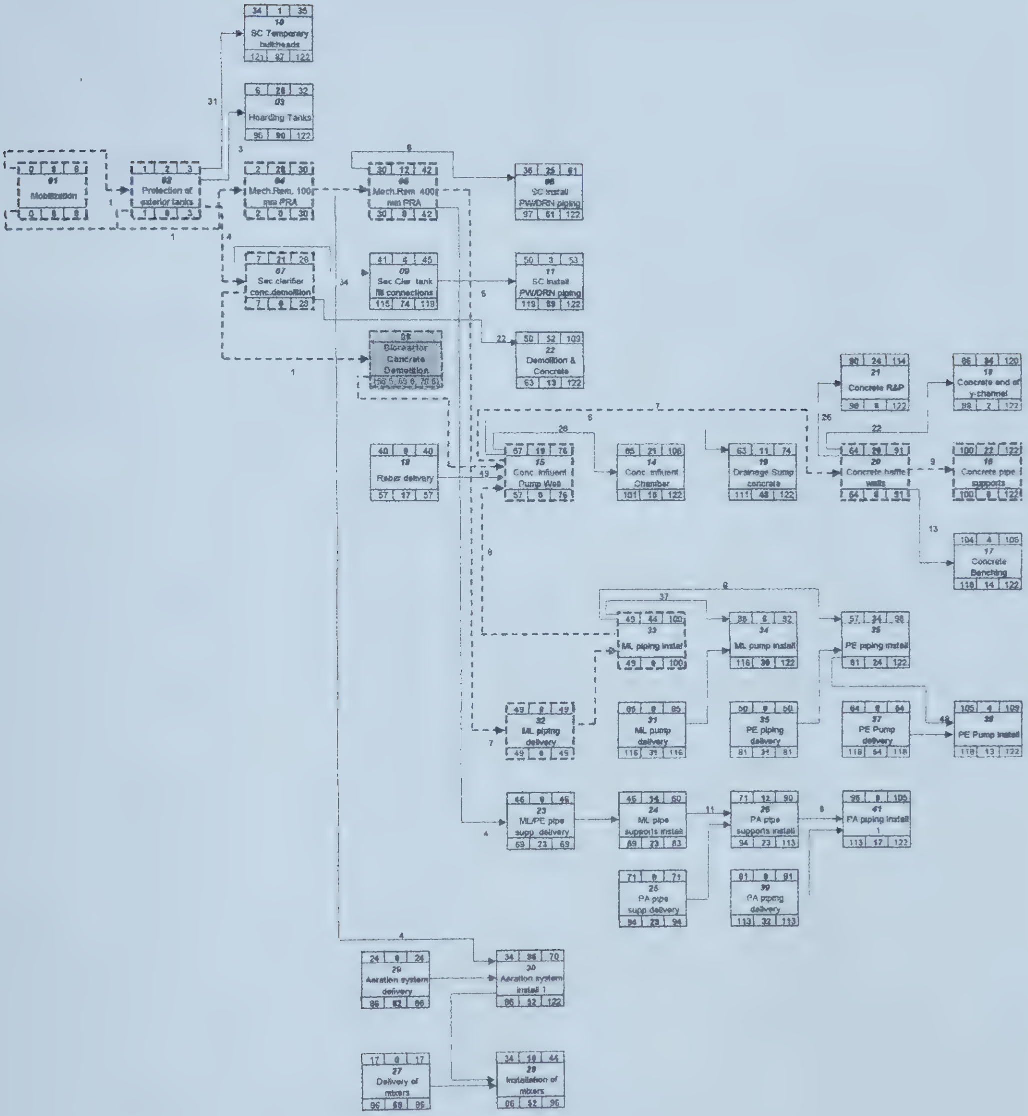


Figure 5.22 Network Diagram Schedule - Snapshot 1 of Case Study

ID	Activity	Original Duration Days	Actual Duration Days	Delay Type	Effect of delays on the progress of the works
1	Mobilization	8	(8.00 , 8.00 , 8.00)		
2	Protection of exterior tanks	2	(2.00 , 2.00 , 2.00)		
3	Hoarding Tanks	26	(26.00 , 26.00 , 26.00)		
4	M. R. - 100 mm PRA coarse bubble aeration diffusers	28	(28.00 , 28.00 , 28.00)		
5	M. R. - Process Air Headers (400 mm PRA)	12	(12.00 , 12.00 , 12.00)		
6	M. R. - 100 mm PA piping	25	(25.00 , 25.00 , 25.00)		
7	Sec. Clarifier Conc. Demolition	21	(21.00 , 21.00 , 21.00)		
8	Bioreactor Concrete Demolition	22	(56.49 , 63.56 , 70.62)	Type 3	This is a critical activity and it suffered a delay Type 3 that has no effect upon the completion of the works due to the fact that only it's start time is critical to the project and it started as planned. It's duration or finish time are not critical to the progress of the works. This activity remains critical to the progress of the work after suffering the delay
9	Sec.Clar. tank fill connections	4	(4.00 , 4.00 , 4.00)		
10	SC Temporary bulkheads	1	(1.00 , 1.00 , 1.00)		
11	SC Install PW/DRN piping	3	(3.00 , 3.00 , 3.00)		
13	Rebar delivery	0	(0.00 , 0.00 , 0.00)		
14	Construction of concrete Influent Chamber	21	(21.00 , 21.00 , 21.00)		
15	Construction of concrete Influent Pump Well	19	(19.00 , 19.00 , 19.00)		
16	Concrete pipe supports	22	(22.00 , 22.00 , 22.00)		
17	Concrete Benching	4	(4.00 , 4.00 , 4.00)		
18	Concrete end of y-channel	34	(34.00 , 34.00 , 34.00)		
19	Drainage Sump concrete	11	(11.00 , 11.00 , 11.00)		
20	Construction of Concrete baffle walls	20	(20.00 , 20.00 , 20.00)		
21	Concrete R&P	24	(24.00 , 24.00 , 24.00)		
22	Demolition & Concrete galleries	52	(52.00 , 52.00 , 52.00)		
23	ML/PE pipe supports delivery	0	(0.00 , 0.00 , 0.00)		
24	ML pipe supports install	14	(14.00 , 14.00 , 14.00)		
25	PA pipe supp.delivery	0	(0.00 , 0.00 , 0.00)		
26	PA pipe supports install	12	(12.00 , 12.00 , 12.00)		
27	Delivery of mixers	0	(0.00 , 0.00 , 0.00)		
28	Installation of submersible propeller type mixer	10	(10.00 , 10.00 , 10.00)		
29	Aeration system delivery	0	(0.00 , 0.00 , 0.00)		
30	Aeration system install	36	(36.00 , 36.00 , 36.00)		
31	ML pump delivery	0	(0.00 , 0.00 , 0.00)		
32	ML piping delivery	0	(0.00 , 0.00 , 0.00)		
33	ML piping install	44	(44.00 , 44.00 , 44.00)		
34	ML pump install	6	(6.00 , 6.00 , 6.00)		
35	PE piping delivery	0	(0.00 , 0.00 , 0.00)		
36	PE piping install	34	(34.00 , 34.00 , 34.00)		
37	PE Pump delivery	0	(0.00 , 0.00 , 0.00)		
38	PE Pump Install	4	(4.00 , 4.00 , 4.00)		
39	PA piping delivery	0	(0.00 , 0.00 , 0.00)		
41	PA piping install 1	9	(9.00 , 9.00 , 9.00)		

Figure 5.23 Effects of Delay on the Schedule - Snapshot 1 of Case Study

5.5.2 Snapshot 2

Snapshot 2 was performed at the beginning of day 11, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 2 (Figure 5.24), a delay has occurred on activity No. 4, "Mechanical Removals - 100 mm PRA coarse bubble aeration". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.3. (Refer to Section 5.2) Figure 5.8 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.25 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 4 and 8). The same is with the activities being affected by the delays or having fuzzy times (Activities No. 1, 2, 5 and 6). The calculations for fuzzy early and finish times are included in Appendix E, Figure E.2. Figure 5.26 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 2 are included in Appendix I.

Activity No. 4, "Mechanical Removals - 100 mm PRA coarse bubble aeration", was critical on the as-planned schedule and remains critical on the actual schedule. The delay it suffered has the effect of delaying the project completion date. The duration of this activity has been extended due to the delay, and it has a finish-to-start relationship

with respect to its succesor activity No. 5, "Mechanical Removals - Process Air Headers (400 mm PRA)". This generated a delay Type 1 on activity No. 5, which is also critical.

The project manager is aware of this situation and decides to take measures in order to mitigate the consequences of this delay. On snapshot 1 schedule, activity No. 5 "Mechanical Removals - Process Air Headers (400 mm PRA)" has a finish-to-start relationship with 7 of days time lag with respect to one of its succesor, activity No. 32, "ML piping delivery", which is also a critical activity. This type of relationship generates a delay Type 1 on activity No. 32. The project manager decided to reschedule activity No. 32 on the snapshot 2 schedule, so that it will start as planned. The relationship time lag with respect to its predecessor, activity No. 5, was reduced from 7 to 5 days. This measure was taken in order to impede the propagation of the delay on the remaining activities of the critical path.

Similar measures were taken with respect to the other successors of activity No. 5, although they are non-critical. On the snapshot 1 schedule, activity No. 5 has a finish-to-start relationship with 4 days of time lag with respect to its successor, activity No. 23, "Mixed Liquor (ML) / Process Effluent (PE) pipe supports delivery". This type of relationship generates a delay Type 1 on activity No. 23. The project manager decided to reschedule activity No. 23 on the snapshot 2 schedule, so that it will start as planned. The relationship time lag with respect to its predecessor, activity No. 5, was reduced from 4 to 2 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path and has enough float to absorb the delay (i.e. 23 days).

On the snapshot 1 schedule, activity No. 5 had start-to-start relationship with 6 days of time lag with respect to its other successor, activity No. 6, "Secondary Clarifier

Install PW/DRN piping". This type of relationship generates a delay Type 1 on activity No. 6. The project manager decided to reschedule activity No. 6 on the snapshot 2 schedule, so that it will start as planned. The relationship time lag with respect to its predecessor, activity No. 5, was reduced from 6 to 4 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path and has enough float to absorb the delay (i.e. 59.85 days).

On the snapshot 1 schedule, activity No. 4 had a finish-to-start relationship with 4 days of time lag with respect to its other successor activity No. 30, "Aeration system install". This type of relationship generates a delay Type 1 on activity No. 30. The project manager decided to reschedule activity No. 30 on the snapshot 2 schedule, so that it will start as planned. The relationship time lag with respect to its predecessor, activity No. 4, was reduced from 4 to 2 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path and has enough float to absorb the delay (i.e. 52 days).

After the measures taken by the project manager, the critical paths remain unchanged. The project completion time on the as-planned schedule was 122 days, and after 10 days of progress the actual project completion time has not been modified.

5.5.3 Snapshot 3

Snapshot 3 was performed at the beginning of day 18, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 3 (Figure 5.27), a delay has occurred on activity No. 3, "Hoarding Tanks". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to Section 5.1). Since

the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.1. (Refer to Section 5.2) Figure 5.6 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.28 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 3 and 8). The delay that affected activity No. 4 has concluded already and its duration in now a crisp value. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.3. Figure 5.29 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 3 are included in Appendix J.

Activity No. 3, "Hoarding Tanks" was non-critical on the as-planned schedule and remains non-critical on the actual schedule. The delay it suffered has no effect upon the completion of the works, due to the float that it has with respect to the project completion date (i.e. 86.82 days). The critical paths remain unchanged. The project completion time on the as-planned schedule was 122 days, and after 17 days of progress the actual project completion time has not been modified.

5.5.4 Snapshot 4

Snapshot 4 was performed at the beginning of day 29, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 4 (Figure 5.30), a delay has occurred on activity No. 7,

"Secondary Clarifier Concrete Demolition". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to Section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.4 (refer to Section 5.2). Figure 5.9 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.31 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 7 and 8). The same is with the activities being affected by the delays or having fuzzy times (Activity No. 22). The delay that affected activity No. 3 has concluded already and its duration in now a crisp value. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.4. Figure 5.32 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 4 are included in Appendix K.

Activity No. 7, "Secondary Clarifier Concrete Demolition" was critical on the as-planned schedule and remains critical on the actual schedule. The delay it suffered has no effect upon the completion of the works due to the fact that only its start time is critical to the project. The extension of its duration, and its finish times are not critical to the project completion time. Since the activity started as planned, its start times are known and are crisp values. The relationship with its only successor on the critical path, activity No. 8 "Bioreactor Concrete Demolition", is a start-to-start relationship. For this reason activity No. 8 also has crisp start times and is not affected by the delay on activity No. 7.

On the snapshot 3 schedule, activity No. 7 has a finish-to-start relationship with 22 days of time lag with respect to its other successor, non-critical activity No. 22, "Demolition & Concrete galleries". This type of relationship generates a delay Type 1 on activity No. 22. The project manager decided to reschedule activity No. 22 on the snapshot 4 schedule, so that it will start as planned. The relationship time lag with respect to its predecessor, activity No. 7, was reduced from 22 to 4 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path.

The critical paths remain unchanged. The project completion time on the as-planned schedule was 122 days, and after 28 days of progress the actual project completion time has not been modified.

5.5.5 Snapshot 5

Snapshot 5 was performed at the beginning of day 46, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 5 (Figure 5.33), a delay has occurred on activity No. 23, "Mixed Liquor (ML) / Process Effluent (PE) pipe supports delivery". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.13. (Refer to Section 5.2) Figure 5.18 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.34 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 7, 8 and 23). The same is with the activities being affected by the delays or having fuzzy times (Activities No. 22, 24 and 26). The calculations for fuzzy early and finish times are included in Appendix E, Figure E.5. Figure 5.35 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 5 are included in Appendix L.

Activity No. 23, "Mixed Liquor (ML) / Process Effluent (PE) pipe supports delivery", was non-critical on the as-planned schedule and remains non-critical on the actual schedule. The delay it suffered does not affect the project completion date due to the fact that the activity belongs to a non-critical path and it has enough float to absorb the delay. (i.e. 22.85 days). The successor of activity No. 23 is activity No. 24, "Mixed Liquor (ML) pipe supports install", and their relationship is finish-to-start with no lag time. Due to this type of relationship, the delay suffered by activity No. 23 generates a delay type 1 on activity No. 24. Activity No. 24 is also a non-critical activity, and the delay it experienced doesn't affect the project completion time either, because this activity belongs to the same non-critical path and it has enough float to absorb the delay. (i.e. 22.85 days).

The successor of activity No. 24 is activity No. 26, "Process Air (PA) pipe supports install", and their relationship on the snapshot 4 schedule is finish-to-start with 11 days of lag time. Due to this type of relationship, the delay suffered by activity No. 24 generates a delay type 1 on activity No. 26. This activity is also is also non-critical, and the delay it would experience doesn't affect the project completion time either. Even though, the

project manager decided to reschedule activity No. 26 on the snapshot 5 schedule, so that it will start as planned. The relationship time lag with respect to its predecessor, activity No. 24, was reduced from 11 to 6 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path.

Activities No. 6 and 28 suffered interruptions that have no effect upon the completion of the works, because these activities belong to non-critical paths and they have enough float to absorb the interruptions (i.e. 55 and 52 days respectively).

The critical paths remain unchanged. The project completion time on the as-planned schedule was 122 days, and after 45 days of progress the actual project completion time has not been modified.

5.5.6 Snapshot 6

Snapshot 6 was performed at the beginning of day 49, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 6 (Figure 5.36), a delay has occurred on activity No. 30, "Aeration system install". The circumstances that originated the delay are described in Figure 6.3. The categorization of this delay is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.14. (Refer to Section 5.2) Figure 5.19 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy

network diagram in Figure 5.37 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 8, 23 and 30). The same is with the activities being affected by the delays or having fuzzy times (Activities No. 22, 24, 26, 27, 28 and 29). The delay that affected activity No. 7 has concluded already and its duration in now a crisp value. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.6. Figure 5.38 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 6 are included in Appendix M.

Activity No. 30, "Aeration system install", was non-critical on the as-planned schedule and remains non-critical on the actual schedule. The delay it suffered has no effect upon the completion of the works, because this activity belongs to a non-critical path, and the float that it has with respect to the project completion date (i.e. 48.64 days) is enough to absorb the delay.

Activities No. 6 and 28 suffered interruptions that have no effect upon the completion of the works, because these activities belong to non-critical paths and they have enough float to absorb the interruptions (i.e. 52 and 48.64 days respectively). The critical paths remain unchanged. The project completion time on the as-planned schedule was 122 days, and after 48 days of progress the actual project completion time has not been modified.

5.5.7 Snapshot 7

Snapshot 7 was performed at the beginning of day 51, in order to update the schedule due the occurrence of delays. As can be observed on the bar chart corresponding to snapshot 7 (Figure 5.39), a delay has occurred on activity No. 3,

"Hoarding Tanks", and another delay has occurred on activity No. 8, "Bioreactor Concrete Demolition". The circumstances that originated the delays are described in Figure 5.3. The categorization of these delays is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delays, the delay duration are not known with certainty and thus they are determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented on Table 5.2 for activity No. 3, "Hoarding Tanks", and on Table 5.6 for activity No. 8, "Bioreactor Concrete Demolition". (Refer to Section 5.2). Figure 5.7 shows the delay duration PDF and membership function for activity No. 3, "Hoarding Tanks", and Figure 5.12 shows the delay duration PDF and membership function for activity No. 8, "Bioreactor Concrete Demolition" (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.40 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 3, 8 and 30). The same is with the activities being affected by the delays or having fuzzy times (Activities No. 27, 28 and 29). The delay that affected activity No. 23 has concluded already and its duration in now a crisp value. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.7. Figure 5.41 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 7 are included in Appendix N.

Activity No. 3, "Hoarding Tanks" was non-critical on the as-planned schedule and remains non-critical on the actual schedule. The delay it suffered has no effect upon the completion of the works, because this activity belongs to a non-critical path, and the float

that it has with respect to the project completion date (i.e. 53.87 days) is enough to absorb the delay.

Activity No. 8, "Bioreactor Concrete Demolition" was critical on the as-planned schedule and remains critical on the actual schedule. The delay it suffered has no effect upon the completion of the works due to the fact that only its start time is critical to the project. The extension of its duration, and its finish times are not critical to the project completion time. Since the activity started as planned, its start times are known and are crisp. The relationship with its only successor, activity No. 15 "Concrete Influent Pump Well", is a start-to-start relationship. For this reason activity No. 15 also has crisp start times and is not affected by the delay on activity No. 8. Due to the delay that activity No. 8 experienced, its duration and finish time are fuzzy.

Activities No. 3, 6 and 28 suffered interruptions that have no effect upon the completion of the works, because these activities belong to non-critical paths and they have enough float to absorb the interruptions (i.e. 53.87, 50 and 48.64 days respectively).

The critical paths remain unchanged. The project completion time on the as-planned schedule was 122 days, and after 50 days of progress the actual project completion time has not been modified.

5.5.8 Snapshot 8

Snapshot 8 was performed at the beginning of day 56, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 8 (Figure 5.42), a delay has occurred on activity No. 8, "Bioreactor Concrete Demolition". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to

section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.7. (Refer to Section 5.2) Figure 5.11 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.43 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 3, and 8). The delay that affected activity No. 30 has concluded already and its duration in now a crisp value. The calculations for fuzzy early and finish times are included in Figure Appendix E, Figure E.8. Figure 5.44 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 8 are included in Appendix O.

Activity No. 8, "Bioreactor Concrete Demolition" was critical on the as-planned schedule and remains critical on the actual schedule. The delay it suffered has no effect upon the completion of the works due to the fact that only its start time is critical to the project. The extension of its duration, and its finish times are not critical to the project completion time. Since the activity started as planned, its start times are known and are crisp. The relationship with its only successor, activity No. 15 "Concrete Influent Pump Well", is a start-to-start relationship. For this reason activity No. 15 also has crisp start times and is not affected by the delay on activity No. 8. Due to the delay that activity No. 8 experienced, its duration and finish time are fuzzy.

Activities No. 6 and 28 suffered interruptions that have no effect upon the completion of the works, because these activities belong to non-critical paths and they have enough float to absorb the interruptions (i.e. 45 and 49 days respectively).

The critical paths remain unchanged. The project completion time on the as-planned schedule was 122 days, and after 55 days of progress the actual project completion time has not been modified.

5.5.9 Snapshot 9

Snapshot 9 was performed at the beginning of day 58, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 9 (Figure 5.45), a delay has occurred on activity No. 15, "Construction of concrete Influent Pump Well". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.9. (Refer to Section 5.2) Figure 5.14 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.46 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 3, 8 and 15). The same is with the activities being affected by the delays or having fuzzy times (Activities No. 14, 16, 17, 18, 19, 20 and 21). The calculations for fuzzy early and finish times are included in

Appendix E, Figure E.9. Figure 5.47 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 9 are included in Appendix P.

Activities No. 6 and 28 suffered interruptions that have no effect upon the completion of the works, because these activities belong to non-critical paths and they have enough float to absorb the interruptions (i.e. 44.07 and 50.07 days respectively).

Activity No. 15, "Construction of concrete Influent Pump Well" was critical on the as-planned schedule and remains critical on the actual schedule. The delay it suffered has the effect of delaying the project completion date. Its start date was delayed and it has start-to-start relationships with respect to all its predecessors, especially with critical activity No. 20, "Concrete Baffle walls". This generates a delay type 1 on activity No. 20 that has the effect of delay the project completion date.

The project manager is aware of this situation and decides to take measures in order to mitigate the consequences of this delay. On the snapshot 8 schedule, Activity No. 20 "Concrete Baffle walls" has a start-to-start relationship with 7 days of lead time with respect to its predecessor, activity No. 15. This type of relationship generates a delay Type 1 on activity No. 20. The project manager decided to reschedule activity No. 20 on the snapshot 9 schedule, so that it will start as planned. The relationship time lead with respect to its predecessor, activity No. 15, was reduced from 7 to 4 days. This measure was taken in order to impede the propagation of the delay on the remaining activities of the critical path.

Similar measures were taken with respect to the other successors of activity No. 15, although they are non-critical. On the snapshot 8 schedule, Activity No. 14 "Concrete Influent Chamber" has a start-to-start relationship with 28 days of lead time with respect to its predecessor, activity No. 15. This type of relationship generates a delay Type 1 on

activity No. 14. The project manager decided to reschedule activity No. 14 on the snapshot 9 schedule, so that it will start as planned. The relationship time lag with respect to its predecessor, activity No. 15, was reduced from 28 to 25 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path and has enough float to absorb the delay (i.e. 16 days).

On the snapshot 8 schedule, Activity No. 19 "Drainage Sump concrete" has a start-to-start relationship with 6 days of lead time with respect to its predecessor, activity No. 15. This type of relationship generates a delay Type 1 on activity No. 19. The project manager decided to reschedule activity No. 19 on the snapshot 9 schedule, so that it will start as planned. The relationship time lag with respect to its predecessor, activity No. 15, was reduced from 6 to 3 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path and has enough float to absorb the delay (i.e. 48 days).

On the snapshot 8 schedule, Activity No. 33 "(Mixed Liquor) ML piping install" has a start-to-start relationship with 8 days of lead time with respect to its successor, activity No. 15. The project manager decided to modify the relationship between activities No. 15 and 33, on the snapshot 9 schedule, to account for the delay in the start of activity No. 15. The relationship time lead was increased from 8 days to 11 days in order to account for the extra time that was employed in the start of activity No. 15.

After the measures taken by the project manager, the critical path remains unchanged and the delay that activity No. 15 suffered was mitigated, so that it had no effect upon the project completion date. Even though, since its start time is a fuzzy value, this value is propagated to the start and finish times of its successors in the critical path. For this reason the project completion time is a fuzzy value as well.

Figure 6.48 displays graphically project duration and critical path times and shows the respective criticality measurements. As can be seen in Figure 5.48, critical path 1 is clearly the most critical path in the project because it has the largest values of Possibility Measure and Agreement Index, (i.e. PM = 1, AI = 1). Critical path 2 is near-critical due to its Possibility Measure and Agreement Index values, (i.e. PM = 0.97, AI = 0.99). Figure 5.49 shows the criticality of the activities in each path. As can be seen in Figure 5.49, activities No. 1, 2, 15, 16 and 20 have the highest degrees of criticality because they are common to both critical paths in the schedule. This indicates the potential of these activities for creating a bottleneck in the schedule. The project completion time on the as-planned schedule was 122 days, and after 57 days of progress the actual project completion time is approximately 122 days, with a definitive minimum time of 119 days and a definitive maximum completion time of 124 days.

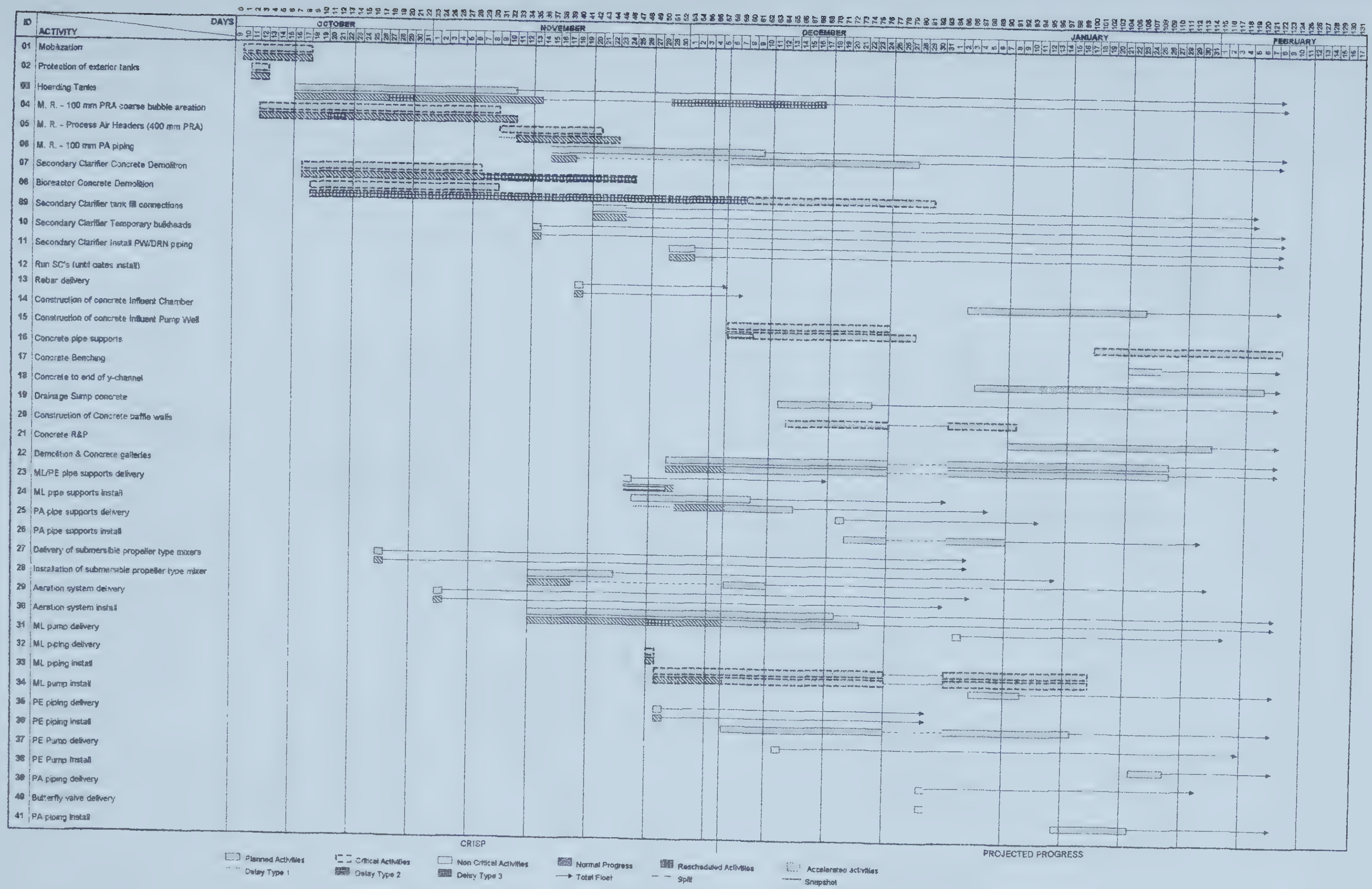


Figure 5.24 Bar Chart Schedule - Snapshot 9 of Case Study

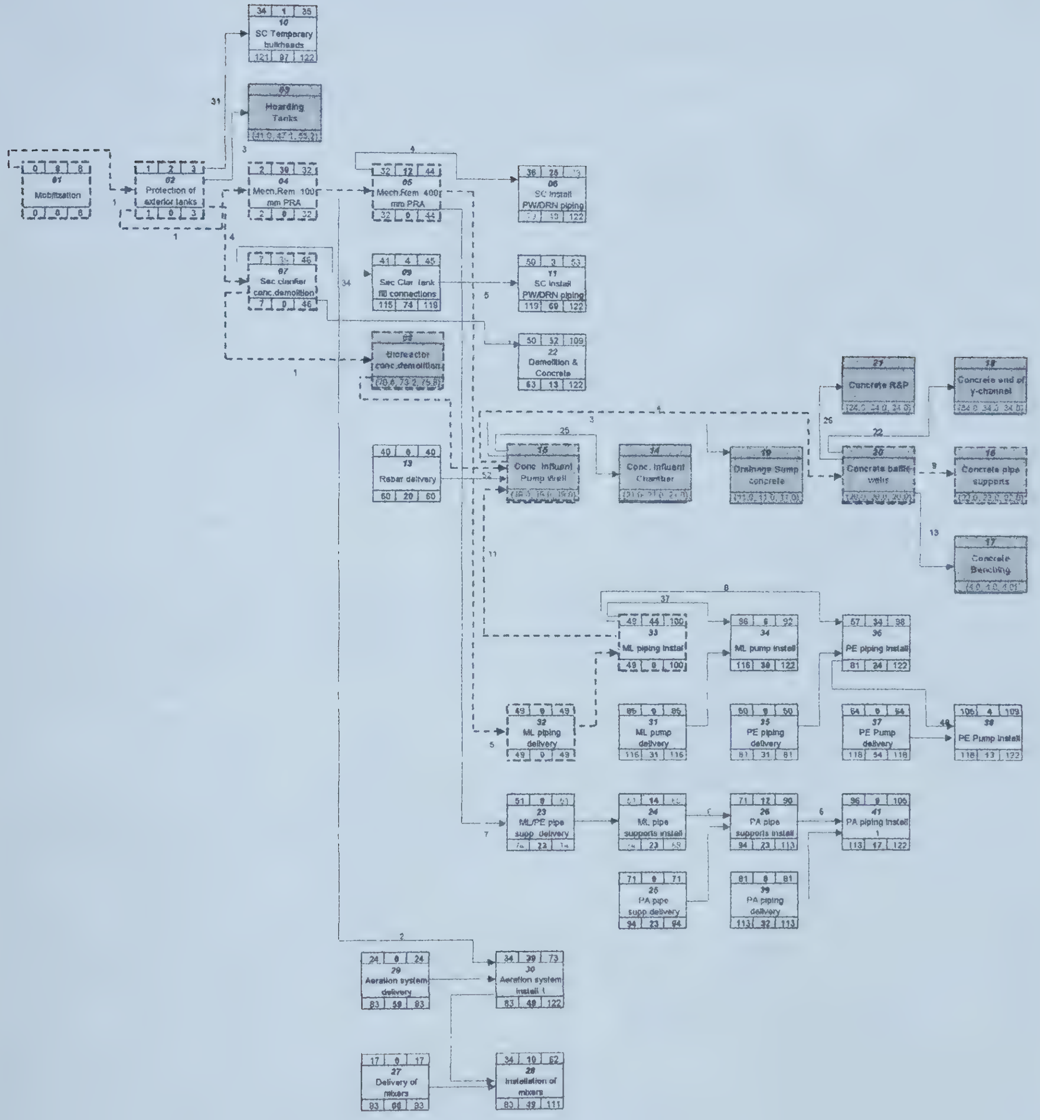
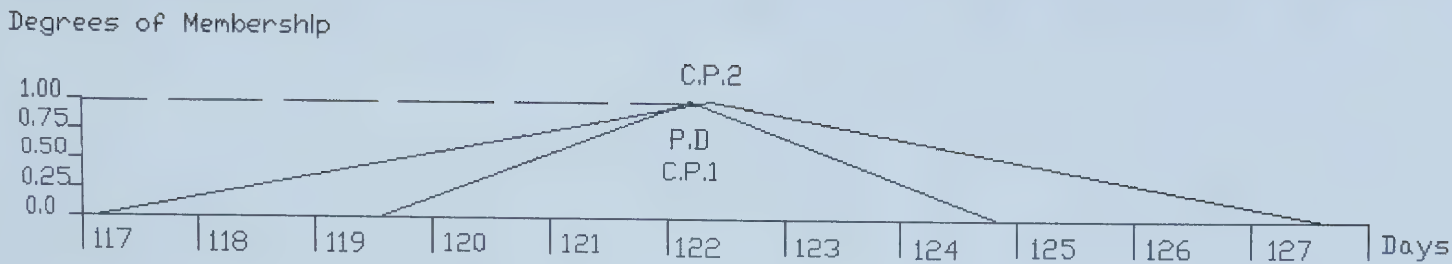


Figure 5.25 Network Diagram Schedule - Snapshot 9 of Case Study

ID	Activity	Original Duration Days	Actual Duration Days	Delay Type	Effect of delays on the progress of the work
1	Mobilization	8	(8.00 , 8.00 , 8.00)		
2	Protection of exterior tanks	2	(2.00 , 2.00 , 2.00)		
3	Hoarding Tanks	26	(41.03 , 47.13 , 53.24)	Type 3	This activity is still suffering the delay
4	M. R. - 100 mm PRA coarse bubble aeration diffusers	28	(30 , 30 , 30)		
5	M. R. - Process Air Headers (400 mm PRA)	12	(12 , 12 , 12)		
6	M. R. - 100 mm PA piping	25	(25 , 25 , 25)		This is a non-critical activity and it suffered an interruption that has no effect upon the completion of the works due to the float that it has with respect to the project completion time.
7	Sec. Clarifier Conc. Demolition	21	(39 , 39 , 39)		
8	Bioreactor Concrete Demolition	22	(70.58 , 73.18 , 75.79)	Type 3	This activity is still suffering the delay. The lag time with respect to it's succesor activity 15, was increased from 49 days to 52 days in order to compensate the delay type 2
9	Sec.Clar. tank fill connections	4	(4 , 4 , 4)		
10	SC Temporary bulkheads	1	(1 , 1 , 1)		
11	SC Install PW/DRN piping	3	(3 , 3 , 3)		
13	Rebar delivery	0	(0 , 0 , 0)		
14	Construction of concrete Influent Chamber	21	(21 , 21 , 21)		This is a non-critical activity and it's lag time with respect to it's predecessor activity 15, was reduced from 28 days to 25 days in order to avoid generating a delay type 1
15	Construction of concrete Influent Pump Well	19	(19 , 19 , 19)	Type 2	This is a critical activity and it suffered a delay Type 2 that delays it's start time but not it's duration. This delay has no effect upon the completion of the works due to the fact that the lag times that it has with respect to it's successors absorbed the delay. This activity remains critical to the progress of the work after suffering the delay
16	Concrete pipe supports	22	(22 , 22 , 22)		
17	Concrete Benching	4	(4 , 4 , 4)		
18	Concrete end of y-channel	34	(34 , 34 , 34)		
19	Drainage Sump concrete	11	(11 , 11 , 11)		This is a non-critical activity and it's lag time with respect to it's predecessor activity 15, was reduced from 6 days to 3 days in order to avoid generating a delay type 1
20	Construction of Concrete baffle walls	20	(20 , 20 , 20)		This is a non-critical activity and it's lag time with respect to it's predecessor activity 15, was reduced from 7 days to 4 days in order to avoid generating a delay type 1.
21	Concrete R&P	24	(24 , 24 , 24)		
22	Demolition & Concrete galleries	52	(52 , 52 , 52)		
23	ML/PE pipe supports delivery	0	(0 , 0 , 0)		
24	ML pipe supports install	14	(14 , 14 , 14)		
25	PA pipe supp delivery	0	(0 , 0 , 0)		
26	PA pipe supports install	12	(12 , 12 , 12)		
27	Delivery of mixers	0	(0 , 0 , 0)		
28	Installation of submersible propeller type mixer	10	(10 , 10 , 10)		This is a non-critical activity and it suffered an interruption that has no effect upon the completion of the works due to the float that it has with respect to the project completion time
29	Aeration system delivery	0	(0 , 0 , 0)		
30	Aeration system install	36	(39 , 39 , 39)		
31	ML pump delivery	0	(0 , 0 , 0)		
32	ML piping delivery	0	(0 , 0 , 0)		
33	ML piping install	44	(44 , 44 , 44)		The lag time with respect to it's succesor activity 15, was increased from 8 days to11 days in order to compensate the delay type 2.
34	ML pump install	6	(6 , 6 , 6)		
35	PE piping delivery	0	(0 , 0 , 0)		
36	PE piping install	34	(34 , 34 , 34)		
37	PE Pump delivery	0	(0 , 0 , 0)		
38	PE Pump Install	4	(4 , 4 , 4)		
39	PA piping delivery	0	(0 , 0 , 0)		
41	PA piping install 1	9	(9 , 9 , 9)		

Figure 5.26 Effects of Delay on the Schedule - Snapshot 9 of Case Study



Critical Paths:

C.P.1=1-2-4-5-32-33-15-20-16
C.P.2=1-2-7-8-15-20-16

Possibility Measure and Agreement Index:

PM1=1.00 AI1=1.00
PM2=0.97 AI2=0.99

Figure 5.27 Project Duration and Critical Paths - Snapshot 9 of Case Study

ID	Activity	PM	ΣPM	AI	ΣAI
1	Mobilization	1.00	1.97	1.00	1.99
2	Protection of exterior tanks	1.00	1.97	1.00	1.99
4	M. R. - 100 mm PRA coarse bubble areation	1.00	1.00	1.00	1.00
5	M. R. - Process Air Headers (400 mm PRA)	1.00	1.00	1.00	1.00
7	Sec. Clarifier Conc. Demolition	0.97	0.97	0.99	0.99
8	Bioreactor Concrete Demolition	0.97	0.97	0.99	0.99
9	Sec.Clar. tank fill connections	0.97	0.97	0.99	0.99
10	SC Temporary bulkheads	0.97	0.97	0.99	0.99
11	SC Install PW/DRN piping	0.97	0.97	0.99	0.99
15	Construction of concrete Influent Pump	1.00	1.97	1.00	1.99
16	Concrete pipe supports	1.00	1.97	1.00	1.99
20	Construction of Concrete baffle walls	1.00	1.97	1.00	1.99
32	ML piping delivery	1.00	1.00	1.00	1.00
33	ML piping install	1.00	1.00	1.00	1.00

Figure 5.28 Criticality of Project Activities - Snapshot 9 of Case Study

5.5.10 Snapshot 10

Snapshot 10 was performed at the beginning of day 61, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 10 (Figure 5.50), a second delay has occurred on activity No. 15, "Construction of concrete Influent Pump Well". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.10. (Refer to Section 5.2) Figure 5.15 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.51 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 3, and 15). The delay that affected activity No. 8, and the first delay that affected activity No. 15, have concluded already and their durations are now crisp values. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.10. Figure 5.52 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 10 are included in Appendix Q.

Activities No. 6, and 28 suffered interruptions that have no effect upon the completion of the works, because these activities belong to non-critical paths and they have enough float to absorb the interruptions (i.e. 40, and 49 days respectively).

Activity No. 15, "Construction of concrete Influent Pump Well" was critical on the as-planned schedule and remains critical on the actual schedule. The second delay it suffered has no effect upon the completion of the works due to the fact that only its start time is critical to the project. The extension of its duration, and its finish times are not critical to the project completion time. Since the delay in its start has concluded, its actual start time is known and is crisp. The relationship that it has with respect to all of its successor activities is start-to-start. For this reason its successor activities also have crisp start times and are not affected by the delay on activity No. 15. Due to the delay that activity No. 15 experienced, its duration and finish times are fuzzy. Activity No. 15 also experienced an interruption, but then again, the extension of its duration has no effect upon the completion of the works due to the fact that only its start time is critical to the project.

Figure 5.53 displays graphically project duration and critical path times and shows the respective criticality measurements. As can be seen in this Figure 5.53, critical path 1 is clearly the most critical path in the project because it has the largest values of Possibility Measure and Agreement Index, (i.e. PM = 1, AI = 1). Critical path 2 is near-critical due to its Possibility Measure and Agreement Index values, (i.e. PM = 0.98, AI = 0.99). Figure 5.54 shows the criticality of the activities in each path. As can be seen in Figure 5.54, activities No. 1, 2, 15, 16 and 20 have the highest degrees of criticality because they are common to both critical paths in the schedule. This indicates the potential of these activities for creating a bottleneck in the schedule.

The project completion time on the as-planned schedule was 122 days, and after 60 days of progress the actual project completion time continues to be 122 days, due to the measures taken to correct the impact of delays.

5.5.11 Snapshot 11

Snapshot 11 was performed at the beginning of day 65, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 11 (Figure 5.55), a delay has occurred on activity No. 20, "Construction of Concrete baffle walls". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.11. (Refer to Section 5.2) Figure 5.10 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.56 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 3, 15 and 20). The same is with the activities being affected by the delays or having fuzzy times (Activities No. 16, 17, 18, and 21). The calculations for fuzzy early and finish times are included in Appendix E, Figure E.11. Figure 5.57 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 11 are included in Appendix R.

Activities No. 6, and 28 suffered interruptions that have no effect upon the completion of the works, because these activities belong to non-critical paths and they have enough float to absorb the interruptions (i.e. 46.04, and 55.04 days respectively).

Activity No. 20, "Construction of Concrete baffle walls" was critical on the as-planned schedule and remains critical on the actual schedule. The start of this activity has

been delayed and consequently its completion time is also delayed. Activity No. 20 has a finish-to-start relationship with respect to its successor activity No. 16, "Concrete pipe supports". This generated a delay Type 1 on activity No. 16. Activity No. 16 is also a critical activity and the delay it suffered has the effect of delaying the project completion date.

Some measures were taken to mitigate the effect of the delay with respect to the other successors of activity No. 20, although they are non-critical. On the snapshot 10 schedule, activity No. 20 has a start-to-start relationship with 13 days of lead time with respect to its successor, activity No. 17 Concrete Benching". This type of relationship generates a delay Type 1 on activity No. 17. The project manager decided to reschedule activity No. 17 on the snapshot 11 schedule, so that it will start as planned. The relationship lead time with respect to its predecessor, activity No. 20, was reduced from 13 to 8 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path and has enough float to absorb the delay (i.e. 19 days).

On the snapshot 10 schedule, activity No. 20 has a start-to-start relationship with 22 days of lead time with respect to its successor, activity No. 18, "Concrete end of y-channel Concrete end of y-channel". This type of relationship generates a delay Type 1 on activity No. 18. The project manager decided to reschedule activity No. 18 on the snapshot 11 schedule, so that it will start as planned. The relationship lead time with respect to its predecessor, activity No. 20, was reduced from 22 to 17 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path and has enough float to absorb the delay (i.e. 7 days).

On the snapshot 10 schedule, activity No. 20 has a start-to-start relationship with 26 days of lead time with respect to its successor, activity No. 21, "Concrete Repair & Patching". This type of relationship generates a delay Type 1 on activity No. 21. The project manager decided to reschedule activity No. 21 on the snapshot 11 schedule, so that it will start as planned. The relationship lead time with respect to its predecessor, activity No. 20, was reduced from 28 to 21 days. This measure was taken in order maintain the start time of this activity, although it belongs to a non-critical path and has enough float to absorb the delay (i.e. 13 days).

Figure 5.58 displays graphically project duration and critical path times and shows the respective criticality measurements. As can be seen in Figure 5.58, critical path 1 is clearly the most critical path in the project because it has the largest values of Possibility Measure and Agreement Index, (i.e. PM = 1, AI = 1). Critical path 2 is near-critical due to its Possibility Measure and Agreement Index values, (i.e. PM = 0.98, AI = 0.99). Figure 5.59 shows the criticality of the activities in each path. As can be seen in Figure 5.59, activities No. 1, 2, 15, 16 and 20 have the highest degrees of criticality because they are common to both critical paths in the schedule. This indicates the potential of these activities for creating a bottleneck in the schedule.

The project completion time on the as-planned schedule was 122 days, and after 64 days of progress the actual project completion time is approximately 127 days, with a definitive minimum time of 125 days and a definitive maximum completion time of 130 days.

5.5.12 Snapshot 12

Snapshot 12 was performed at the beginning of day 86, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 12 (Figure 5.60), a delay has occurred on activity No. 14, "Construction of concrete Influent Chamber". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.8. (Refer to Section 5.2) Figure 5.13 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.61 incorporates actual durations. Activities experiencing delays that have fuzzy durations are shaded (Activities No. 14 and 15). The delays that affected activity No. 3, and activity No. 20, have concluded already and their durations are now crisp values. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.12. Figure 5.62 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 12 are included in Appendix S.

Activities No. 6, 22, 26, 28, and 36 suffered interruptions that have no effect upon the completion of the works, because these activities belong to non-critical paths and they have enough float to absorb the interruptions (i.e. 29, 17, 26, 41 and 25 days respectively). Critical activity No. 33 also experienced an interruption, the extension of its

duration has no effect upon the project completion date due to the fact that only its start time is critical to the project.

Activity No. 14, "Construction of concrete Influent Chamber" was non-critical on the as-planned schedule and remains non-critical on the actual schedule. The delay it suffered has no effect upon the completion of the works, due to the float that it has with respect to the project completion date (i.e. 17.96 days).

Activity No. 20, "Construction of Concrete baffle walls", was a critical on the as-planned schedule and remains critical on the actual schedule. Activity No. 20 suffered an interruption that has the effect of delaying the project completion date due to the fact that it generates another delay Type 1 on activity No. 16. Activity No. 16, "Concrete pipe supports", is also a critical activity and the delay it suffered has the effect of delaying the project completion date.

Figure 5.63 displays graphically project duration and critical path times and shows the respective criticality measurements. As it can be seen in this Figure, critical path 1 is clearly the most critical path in the project because it has the largest values of Possibility Measure and Agreement Index, (i.e. PM = 1, AI = 1). Critical path 2 is near-critical due to its Possibility Measure and Agreement Index values, (i.e. PM = 0.98, AI = 0.99). Figure 5.64 shows the criticality of the activities in each path. As can be seen in Figure 5.64, activities No. 1, 2, 15, 16 and 20 have the highest degrees of criticality because they are common to both critical paths in the schedule. This indicates the potential of these activities for creating a bottleneck in the schedule.

The project completion time on the as-planned schedule was 122 days, and after 85 days of progress the actual project completion time is 131 days.

5.5.13 Snapshot 13

Snapshot 13 was performed at the beginning of day 108, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 13 (Figure 5.65), a delay has occurred on activity No. 34, "Mixed Liquor (ML) pump install". The circumstances that originated the delay are described in Figure 5.15. The categorization of this delay is shown in Figure 5.20 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure are presented in Table 5.15. (Refer to Section 5.2) Figure 5.10 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (Refer to Section 5.4). The fuzzy network diagram in Figure 5.66 incorporates actual durations. The activity experiencing delays that has fuzzy duration is shaded (Activity No. 34). The same is with the activity No. 31 that has fuzzy times. The delays that affected activity No. 14, and activity No. 15, have concluded already and their durations are now crisp values. Activity No. 16, "Concrete pipe supports" is still suffering the delay Type 1 that has the effect of delaying the project completion date. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.13. Figure 5.67 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 13 are included in Appendix T.

Activity No. 34, "Mixed Liquor (ML) pump install", was non-critical on the as-planned schedule and remains non-critical on the actual schedule. The delay it suffered has no effect upon the completion of the works, due to the float that it has with respect to the project completion date (i.e. 16.85 days).

Activities No. 6, 22, 26, 28, 34 and 36 suffered interruptions that have no effect upon the completion of the works, because these activities belong to non-critical paths and they have enough float to absorb the interruptions (i.e. 7, 16, 26, 22, 16.85 and 9 days respectively). Critical activity No. 33 also experienced an interruption, the extension of its duration has no effect upon the project completion date due to the fact that only its start time is critical to the project.

The critical paths remains unchanged. The project completion time on the as-planned schedule was 122 days, and after 107 days of progress the actual project completion time is 131 days.

5.5.14 Snapshot 14

Snapshot 14 was performed at the beginning of day 115, in order to update the schedule due the occurrence of a delay. As can be observed on the bar chart corresponding to snapshot 14 (Figure 5.68), a delay has occurred on activity No. 21, "Concrete Repair & Patch". The circumstances that originated the delay are described in Figure 5.3. The categorization of this delay is shown in Figure 5.4 (refer to section 5.1). Since the date of the snapshot corresponds to the date of the occurrence of the delay, the delay duration is not known with certainty and thus it is determined by means of the delay impact estimation procedure. The delay-sensitive attributes employed in the procedure

are presented in Table 5.12 (refer to Section 5.2) Figure 5.17 shows the delay duration PDF and membership function (refer to Section 5.3)

The fuzzy values of delay duration are shown in Table 5.19 and they are used to revise the activity durations shown in Table 5.20. (refer to Section 5.4). The fuzzy network diagram in Figure 5.69 incorporates actual durations. The activity experiencing delays that has fuzzy duration is shaded (Activity No. 21). The delay that affected activity No. 34 has concluded already and its duration is now a crisp value. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.14. Figure 5.70 indicates the effects of the delay on the schedule. The as-built database records corresponding to snapshot 14 are included in Appendix U.

Activity No. 21, "Concrete Repair & Patch", was non-critical on the as-planned schedule and remains non-critical on the actual schedule. The delay it suffered has no effect upon the completion of the works, due to the float that it has with respect to the project completion date (i.e. 12.83 days).

Activity No. 6, "Mechanical Removals - 100 mm PA" piping was previously a non-critical activity and it suffered two interruptions that have the effect of delaying the project completion date, because these interruptions consumed the available float time. This activity turned critical to the progress of the works after suffering the interruptions in the snapshot schedule 14, and it generated a third critical path that is comprised by activities 1-2-4-5-6. The project completion time on the as-planned schedule was 122 days, and after 114 days of progress the actual project completion time is 131 days.

5.5.15 Snapshot 15

Snapshot 15 was performed at the end of day 130, in order to determine the as-built schedule. As can be observed on the bar chart corresponding to snapshot 15 (Figure 5.71), all activities are now completed. Since the date of the snapshot corresponds to the date of project completion, all activity durations are known with certainty and thus are crisp values.

The fuzzy network diagram in Figure 5.72 incorporates as-built durations. The calculations for fuzzy early and finish times are included in Appendix E, Figure E.15. Figure 5.73 indicates the final effects of previous delays on the schedule. Figure 5.74 is the cause/effect matrix that depicts the aggregated effect that the entire delays generated on the schedule. Figure 5.75 shows the as-planned schedule and the as-built schedule that contains all delays that affected project activities. The as-built database records corresponding to snapshot 15 are included in Appendix V.

The project completion time on the as-planned schedule was 122 days, and the as-built project completion time is 131 days.

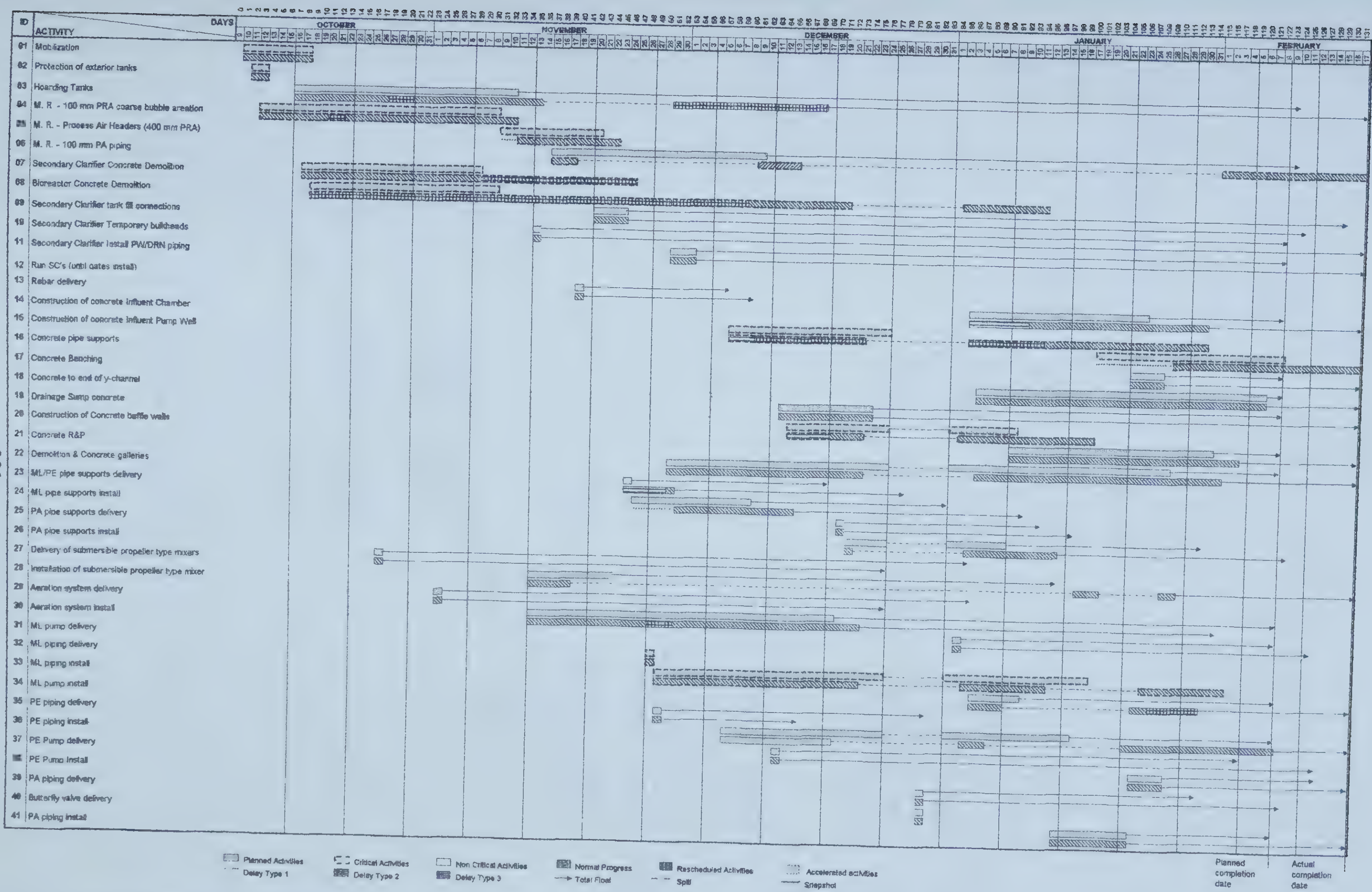


Figure 5.29 Bar Chart Schedule - Snapshot 15 of Case Study

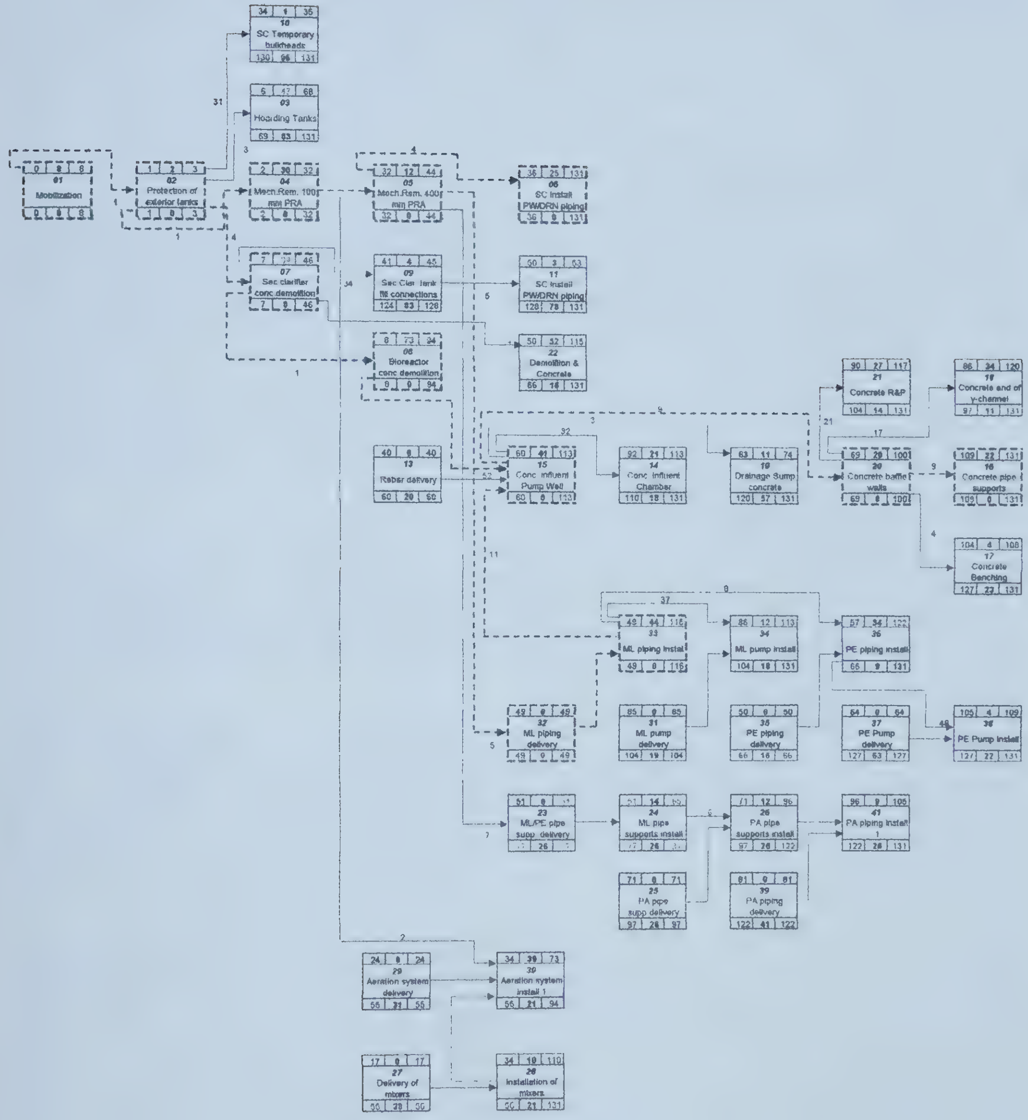


Figure 5.30 Network Diagram Schedule - Snapshot 15 of Case Study

ID	Activity	Original Duration Days	Actual Duration Days	Delay Type	Effect of delays on the progress of the work
1	Mobilization	8	(8.00 , 8.00 , 8.00)		
2	Protection of exterior tanks	2	(2.00 , 2.00 , 2.00)		
3	Hoarding Tanks	26	(47.00 , 47.00 , 47.00)		
4	M. R. - 100 mm PRA coarse bubble aeration diffusers	28	(30.00 , 30.00 , 30.00)		
5	M. R. - Process Air Headers (400 mm PRA)	12	(12.00 , 12.00 , 12.00)		
6	M. R. - 100 mm PA piping	25	(25.00 , 25.00 , 25.00)		This activity was previously a non-critical activity and it suffered two interruptions that have the effect of delaying the project completion date. This activity turned critical to the progress of the works after suffering the interruptions
7	Sec. Clarifier Conc. Demolition	21	(39.00 , 39.00 , 39.00)		
8	Bioreactor Concrete Demolition	22	(73.00 , 73.00 , 73.00)		
9	Sec.Clar. tank fill connections	4	(4.00 , 4.00 , 4.00)		
10	SC Temporary bulkheads	1	(1.00 , 1.00 , 1.00)		
11	SC Install PW/DRN piping	3	(3.00 , 3.00 , 3.00)		
13	Rebar delivery	0	(0.00 , 0.00 , 0.00)		
14	Construction of concrete Influent Chamber	21	(21.00 , 21.00 , 21.00)		
15	Construction of concrete Influent Pump Well	19	(41.00 , 41.00 , 41.00)		
16	Concrete pipe supports	22	(22.00 , 22.00 , 22.00)	Type 1	This activity is critical and it suffered two delays Type 1 that have the effect of delaying the project completion date. This activity remains critical to the progress of the works after suffering the delays
17	Concrete Benching	4	(4.00 , 4.00 , 4.00)		
18	Concrete end of y-channel	34	(34.00 , 34.00 , 34.00)		
19	Drainage Sump concrete	11	(11.00 , 11.00 , 11.00)		
20	Construction of Concrete baffle walls	20	(20.00 , 20.00 , 20.00)		
21	Concrete R&P	24	(27.00 , 27.00 , 27.00)		This is a non-critical activity and it suffered a delay Type 3 that has concluded already. This activity remains non-critical to the progress of the work after suffering the delay
22	Demolition & Concrete galleries	52	(52.00 , 52.00 , 52.00)		
23	ML/PE pipe supports delivery	0	(0.00 , 0.00 , 0.00)		
24	ML pipe supports install	14	(14.00 , 14.00 , 14.00)		
25	PA pipe supp.delivery	0	(0.00 , 0.00 , 0.00)		
26	PA pipe supports install	12	(12.00 , 12.00 , 12.00)		
27	Delivery of mixers	0	(0.00 , 0.00 , 0.00)		
28	Installation of submersible propeller type mixer	10	(10.00 , 10.00 , 10.00)		
29	Aeration system delivery	0	(0.00 , 0.00 , 0.00)		
30	Aeration system install	36	(39.00 , 39.00 , 39.00)		
31	ML pump delivery	0	(0.00 , 0.00 , 0.00)		
32	ML piping delivery	0	(0.00 , 0.00 , 0.00)		
33	ML piping install	44	(44.00 , 44.00 , 44.00)		
34	ML pump install	6	(12.00 , 12.00 , 12.00)		
35	PE piping delivery	0	(0.00 , 0.00 , 0.00)		
36	PE piping install	34	(34.00 , 34.00 , 34.00)		
37	PE Pump delivery	0	(0.00 , 0.00 , 0.00)		
38	PE Pump Install	4	(4.00 , 4.00 , 4.00)		
39	PA piping delivery	0	(0.00 , 0.00 , 0.00)		
41	PA piping install 1	9	(9.00 , 9.00 , 9.00)		

Figure 5.31 Effects of Delay on the Schedule - Snapshot 15 of Case Study

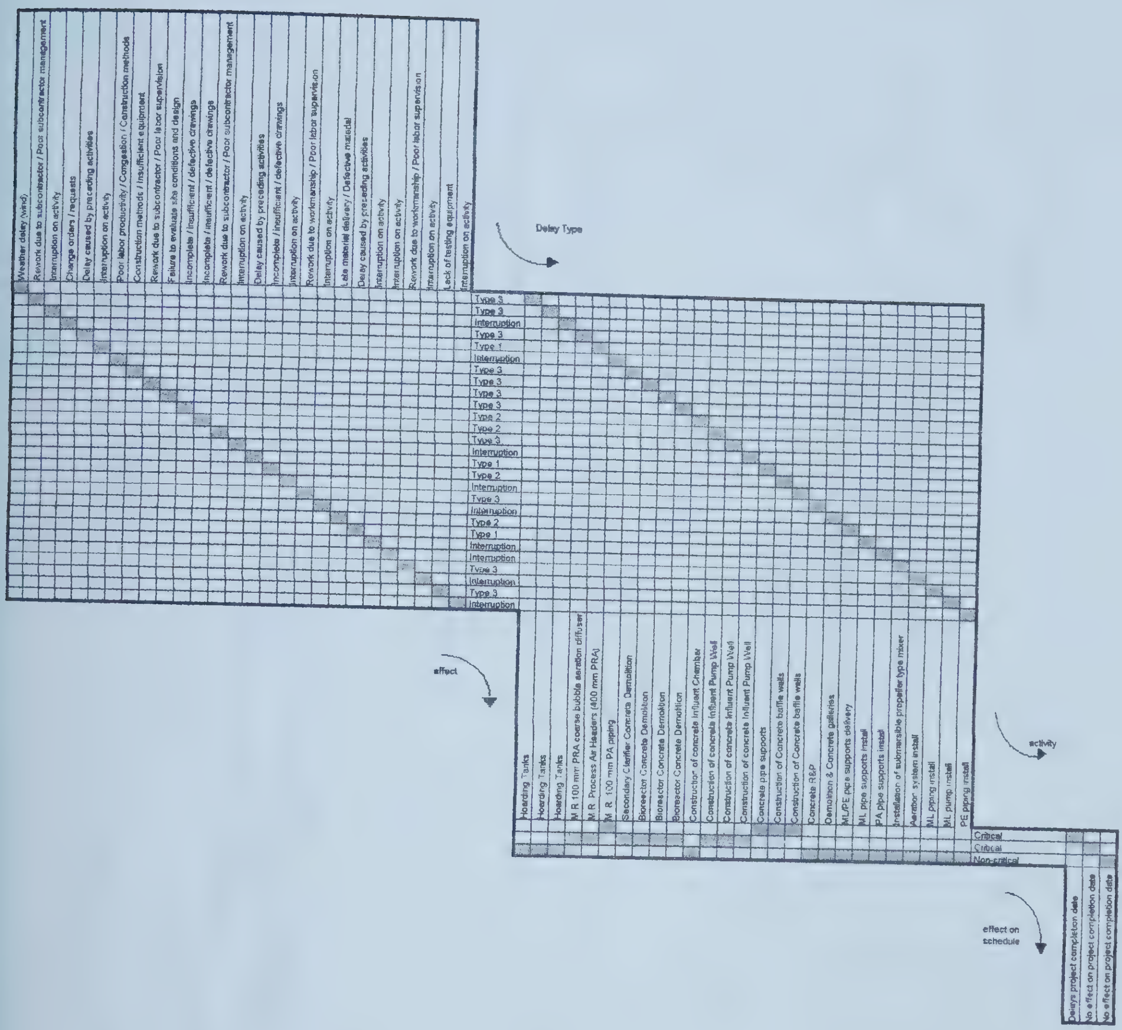


Figure 5.32 Cause-effect matrix. Effects of delays on the schedule for Case Study

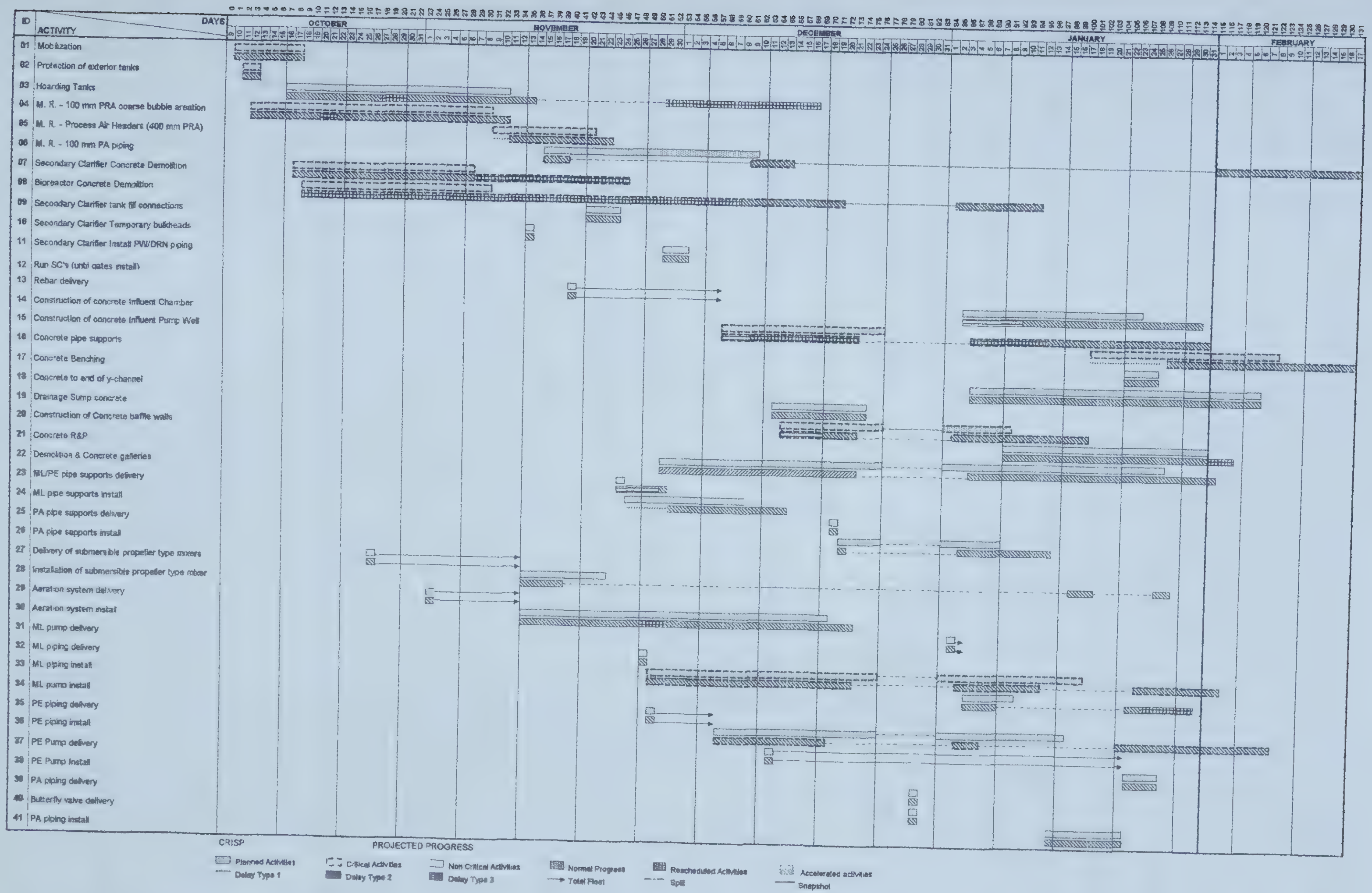


Figure 5.33 As-Planned vs As-Built Schedule

5.6 Summary

In this chapter, a case study project was analyzed with the purpose of validating the effectiveness of the fuzzy logic model presented in Chapter 3. The case study project consisted of retrofitting the existing Bioreactors and Secondary Clarifiers of a local wastewater treatment plant. The project is comprised of forty activities. The as-planned project duration was 122 days, and it was scheduled to be completed on February 8, 2001. Fifteen snapshots were performed at different points in time in order to update the schedule based on the occurrence of delays. The cumulative effect of the delays that affected project activities extended the project duration to 131 days. The project was completed on completed on February 17, 2001. Therefore, as of snapshot 15, the project completion date had slipped by nine days.

The starting point of the analysis was the as-planned schedule derived in Chapter 5. The as-planned schedule was sequentially updated each time a delay occurred on a project activity, based on the actual information describing the occurrences of delays and the actual construction sequence. This information is contained in the as-built database created for the project. In each snapshot, the measures that project management took in order to deal with the negative impact of delays were incorporated. The status of project activities was reconstructed so that each snapshot correctly portrayed the actions taken and the activities occuring at different construction stages. The analysis shows sequentially how the project evolved from the as-planned schedule to the as-built schedule.

The as-built schedule derived by the fuzzy logic model in the last snapshot coincided with the as-built schedule prepared initially for the project. This indicates that the delay durations predicted by the fuzzy logic model were in close agreement with the

delay durations observed on site. This fact also indicates that the fuzzy network scheduling technique used to update the schedule is efficient and produces realistic results. Consequently, the fuzzy logic model proposed in this research is a useful tool that handles the uncertainty associated with predicting the likely consequences of delaying events, and produces realistic progress forecasts that can be used as a basis for planning remaining work in the schedule.

CHAPTER 6 SENSITIVITY ANALYSIS

6.1 Sensitivity Analysis of the Delay Impact Estimation Procedure

A sensitivity analysis was performed in order to evaluate the sensitivity of the delay impact estimation procedure to membership values in the definition of the linguistic variables. As mentioned in Section 5.2, the determination of delay duration for the activities in the case study was performed using the membership values presented by Smith and Hancher6 (1989) in their proposed methodology. In order to perform the sensitivity analysis, the estimation of the delay duration for activity Secondary Clarifier Concrete Demolition was solved again while varying the following parameters:

- Parameter 1: Minor variation in the membership values that define the linguistic variables describing the fuzzy relation between the frequency of occurrence and adverse consequences.

The delay duration was originally determined using the membership functions shown in Table 6.1, defining the linguistic variables that describe the fuzzy relation between the frequency of occurrence and the adverse consequences. Figure 6.1 is a graphical representation of the membership functions used. These membership values are the ones utilized by Smith and Hancher (1989) in their proposed methodology. A second estimation of the delay duration was performed using the set of membership functions shown in Table 6.2. Figure 6.2 is a graphical representation of the membership functions used. A third estimation of the delay duration was performed using the set of membership functions shown in Table 6.3. Figure 6.3 is a graphical representation of the membership functions used.

Table 6.1 Membership functions for original duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 1

Elements	*Membership Value*				
0	0.0	0.0	0.0	1.0	0.0
0.1	0.0	0.0	0.5	0.7	0.0
0.2	0.0	0.0	0.9	0.1	0.0
0.3	0.0	0.1	0.9	0.0	0.0
0.4	0.0	0.7	0.5	0.0	0.0
0.5	0.0	1.0	0.0	0.0	0.0
0.6	0.5	0.7	0.0	0.0	0.0
0.7	0.9	0.1	0.0	0.0	0.0
0.8	0.9	0.0	0.0	0.0	0.1
0.9	0.5	0.0	0.0	0.0	0.7
1	0.0	0.0	0.0	0.0	1.0
Linguistic Variable	Large	Medium	Small	Very Small	Very Large

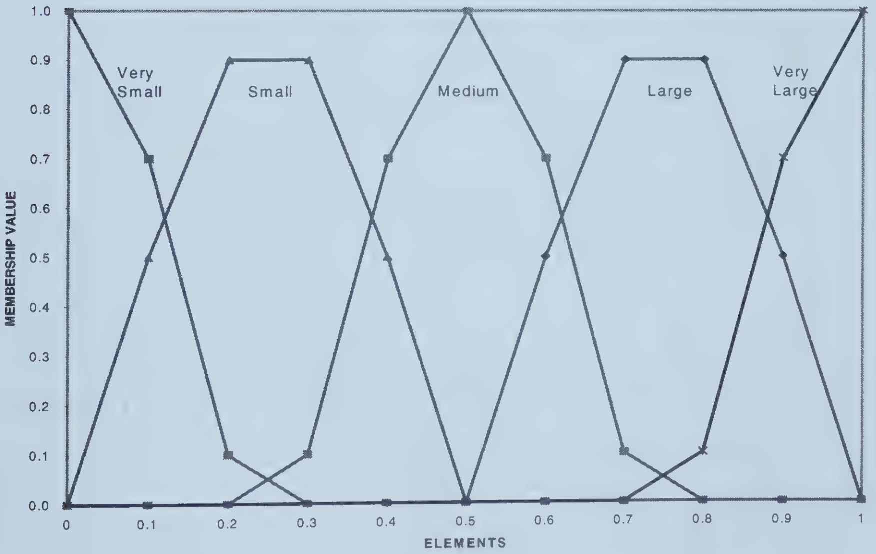


Figure 6.1 Membership functions for original duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 1. Smith and Hancher (1989).

Table 6.2 Membership functions for second duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 1

Elements	*Membership Value*				
0	0.0	0.0	0.1	1.0	0.0
0.1	0.0	0.0	0.7	0.9	0.0
0.2	0.0	0.1	0.9	0.5	0.0
0.3	0.0	0.3	0.9	0.1	0.0
0.4	0.0	0.8	0.7	0.0	0.0
0.5	0.1	1.0	0.1	0.0	0.0
0.6	0.7	0.8	0.0	0.0	0.0
0.7	0.9	0.3	0.0	0.0	0.1
0.8	0.9	0.1	0.0	0.0	0.5
0.9	0.7	0.0	0.0	0.0	0.9
1	0.1	0.0	0.0	0.0	1.0
Linguistic Variable	Large	Medium	Small	Very Small	Very Large

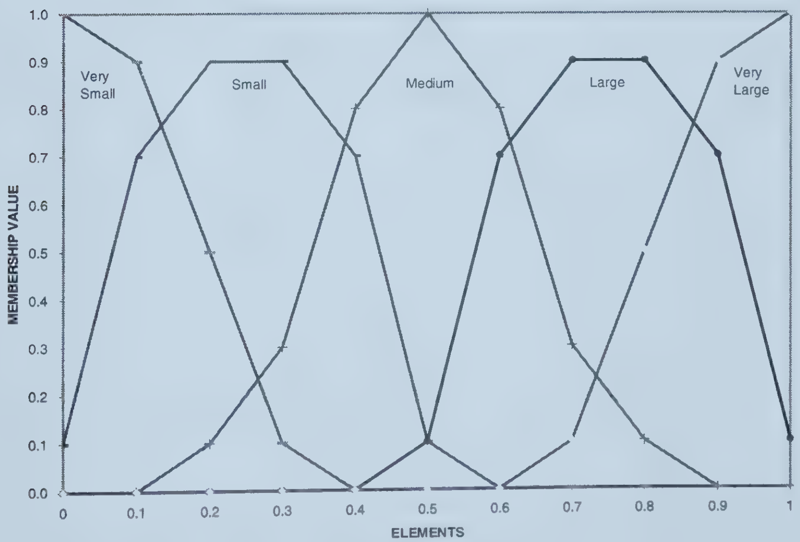


Figure 6.2 Membership functions for second duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 1

Table 6.3 Membership functions for third duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 1

Elements	*Membership Value*				
0	0.0	0.0	0.0	1.0	0.0
0.1	0.0	0.0	0.5	0.7	0.0
0.2	0.0	0.1	0.9	0.1	0.0
0.3	0.0	0.6	1.0	0.0	0.0
0.4	0.0	0.9	0.9	0.0	0.0
0.5	0.5	1.0	0.5	0.0	0.0
0.6	0.9	0.9	0.0	0.0	0.0
0.7	1.0	0.6	0.0	0.0	0.0
0.8	0.9	0.1	0.0	0.0	0.1
0.9	0.5	0.0	0.0	0.0	0.7
1	0.0	0.0	0.0	0.0	1.0
Linguistic Variable	Large	Medium	Small	Very Small	Very Large

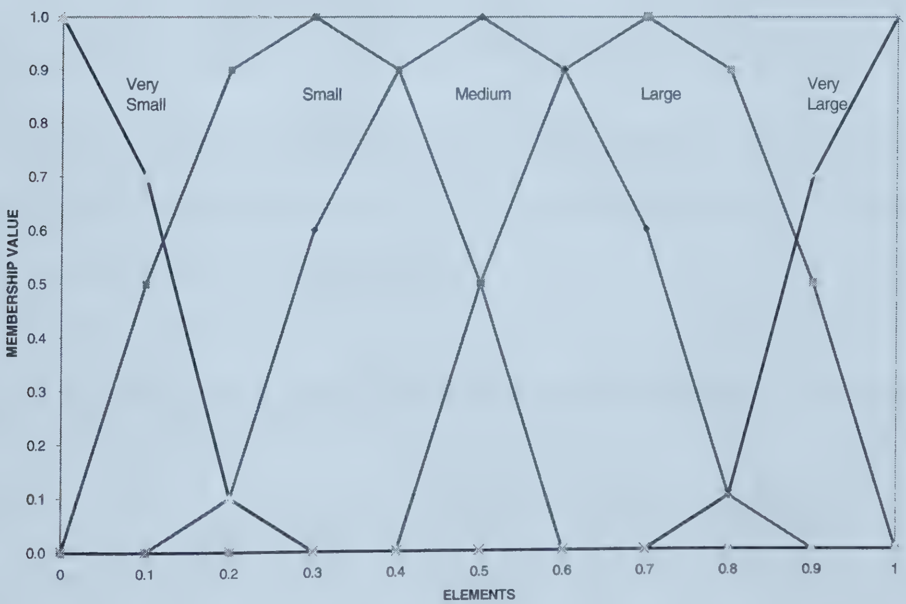


Figure 6.3 Membership functions for third duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 1

As can be seen in Figures 6.1, 6.2 and 6.2, the overlap between the membership functions was increased gradually for each set of membership functions. Table 6.4 summarizes the results of the three duration estimates. The coefficient of variation (COV) was calculated for each delay duration estimate. The COV is a nondimensional quantity that is calculated as the ratio of the mean delay duration and its corresponding standard deviation. The COV measures the uncertainty in the delay duration estimate. (Ayyub and Haldar, 1984).

Table 6.4 Results of delay duration estimates for Parameter 1

	Mean [days]	**Std. Dev.** [days]	**COV**
Original Estimate	18.36	1.54	0.084
Second Estimate	18.50	1.40	0.075
Third Estimate	17.40	2.10	0.121

The mean, standard deviation and COV values obtained in the second and third estimates were compared with respect to that of the original delay duration estimation. Table 6.5 shows the percent deviation obtained:

Table 6.5 Percent deviation in the results of delay duration estimates for Parameter 1

	Mean	**Std. Dev.**	**COV**
Second Estimate	0.64%	-3.16%	-3.82%
Third Estimate	-5.50%	26.50%	30.30%

By comparing the percent deviations of the second estimate in Table 6.5, it can be concluded that the delay impact estimation procedure is not sensitive to small variations

in the membership values that define the linguistic variables describing the fuzzy relation between the frequency of occurrence and adverse consequences. On the other hand, by observing the percent deviations of the third estimate in Table 6.4, it can be concluded that the delay impact estimation procedure is sensitive to large variations in this set of membership values. By observing the COV values in Table 6.4, it can be concluded that the second estimate is the least uncertain of the three duration estimates, and the third estimate is the most uncertain estimate.

- Parameter 2: Major variation in the membership values that define the linguistic variables describing the fuzzy relation between the frequency of occurrence and adverse consequences.

The delay duration was originally determined using the membership functions shown in Table 6.1, defining the linguistic variables that describe the fuzzy relation between the frequency of occurrence and the adverse consequences. These membership values are the ones utilized by Smith and Hancher (1989) in their proposed methodology. A second estimation of the delay duration was performed using the set of membership functions shown in Table 6.6. Figure 6.4 is a graphical representation of the two sets of membership functions used. These membership values are the ones utilized by Ayyub and Haldar (1984) in their proposed methodology. As can be seen on Figures 6.1 and 6.4, the membership sets proposed by Smith and Hancher are radically different form the membership sets proposed by Ayyub and Haldar. Each set of membership functions was proposed by different experts, and correspond to different translations of linguistic variables into fuzzy sets. Table 6.7 summarizes the results of the two duration estimates.

Table 6.6 Membership functions for second duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 2

Elements	*Membership Value*				
0	0.00	0.00	1.00	1.0	0.00
0.1	0.00	0.00	0.90	0.81	0.00
0.2	0.00	0.00	0.50	0.25	0.00
0.3	0.00	0.20	0.00	0.0	0.00
0.4	0.00	0.80	0.00	0.0	0.00
0.5	0.00	1.00	0.00	0.0	0.00
0.6	0.00	0.80	0.00	0.0	0.00
0.7	0.00	0.20	0.00	0.0	0.00
0.8	0.50	0.00	0.00	0.0	0.25
0.9	0.90	0.00	0.00	0.0	0.81
1	1.00	0.00	0.00	0.0	1.00
Linguistic Variable	Large	Medium	Small	Very Small	Very Large

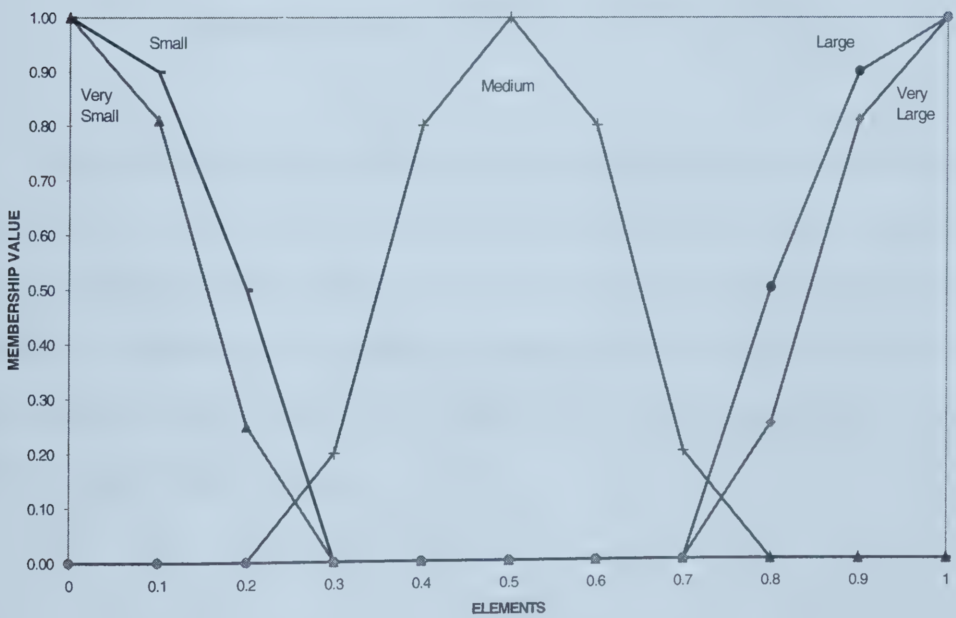


Figure 6.4 Membership functions for second duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 2. Ayyub and Haldar (1984).

Table 6.7 Results of delay duration estimates for Parameter 2

	Mean [days]	Std. Dev. [days]	COV
Original Estimate	18.36	1.54	0.084
Second Estimate	19.14	1.08	0.057

The mean, standard deviation and COV values obtained in the second estimate were compared with respect to that of the original delay duration estimation. Table 6.8 shows the percent deviation obtained:

Table 6.8 Percent deviation in the results of delay duration estimates for Parameter 2

	Mean	Std. Dev.	COV
Second Estimate	4.10%	-42.69%	-48.79%

By comparing the percent deviations of the second estimate in Table 6.8, it can be concluded that the delay impact estimation procedure is sensitive to major variations in the membership values that define the linguistic variables describing the fuzzy relation between the frequency of occurrence and adverse consequences. By observing the COV values in Table 6.7, it can be concluded that the second estimate is less uncertain than the original duration estimate.

• Parameter 3: Variation in the membership values that define the linguistic variables describing the fuzzy relation between the adverse consequences and the delay duration.

The delay duration was originally determined using the membership functions shown in Table 6.9, defining the linguistic variables that describe the fuzzy relation between the adverse consequences and the delay duration. These membership values are the ones utilized by Smith and Hancher (1989) in their proposed methodology. A second estimation of the delay duration was performed using the set of membership functions shown in Table 6.10. A third estimation of the delay duration was performed using the set of membership functions shown in Table 6.11. These membership values are the ones utilized by Ayyub and Haldar (1984) in their proposed methodology. Table 6.12 summarizes the results of the two duration estimates.

Table 6.9 Membership functions for original duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 3. Smith and Hancher (1989).

	Membership Value		
Duration Elements	**Very Large**	**Large**	**Very Small**
14	0	0	0.9
16	0.2	0.2	0.7
18	0.8	0.9	0.1
20	0.9	0.8	0.0
Adverse Consequences	Large	Medium	Small

Table 6.10 Membership functions for second duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 3

	Membership Value		
Duration Elements	**Very Large**	**Large**	**Very Small**
14	0	0	1.0
16	0.3	0.3	0.9
18	0.9	0.9	0.3
20	1.0	0.7	0.0
Adverse Consequences	Large	Medium	Small

Table 6.11 Membership functions for third duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 3. Ayyub and Haldar (1984).

	Membership Value		
Duration Elements	**Very Large**	**Large**	**Very Small**
14	0.00	0.00	1.00
16	0.04	0.20	0.25
18	0.64	0.80	0.04
20	1.00	1.00	0.00
Adverse Consequences	Large	Medium	Small

Table 6.12 Results of delay duration estimates for Parameter 3

	Mean [days]	**Std. Dev.** [days]	**COV**
Original Estimate	18.36	1.54	0.084
Second Estimate	18.38	1.59	0.086
Third Estimate	19.11	2.23	0.117

The mean, standard deviation and COV values obtained in the second and third estimates were compared with respect to that of the original delay duration estimation. Table 6.13 shows the percent deviation obtained:

Table 6.13 Percent deviation in the results of delay duration estimates for Parameter 3

	Mean	Std. Dev.	COV
Second Estimate	0.12%	2.80%	2.68%
Third Estimate	3.93%	30.78%	27.95%

By comparing the percent deviations of the second estimate in Table 6.13, it can be concluded that the delay impact estimation procedure is not sensitive to small variations in the membership values that define the linguistic variables describing the fuzzy relation between the adverse consequences and the delay duration. On the other hand, by observing the percent deviations of the third estimate in Table 6.13, it can be concluded that the delay impact estimation procedure is sensitive to large variations in this set of membership values. By observing the COV values in Table 6.12, it can be concluded that the original estimate is the least uncertain of the three duration estimates, and the third estimate is the most uncertain estimate.

- Parameter 4: Utilization of a different fuzzy relation between adverse consequences and delay duration.

The delay duration was originally determined using the membership functions shown in Table 6.14, defining the linguistic variables that describe the fuzzy relation between the adverse consequences and the delay duration. These membership values are the ones utilized by Smith and Hancher (1989) in their proposed methodology. The original fuzzy relation can be interpreted as: "If the consequences are large, then the delay duration is very large. If the consequences are medium, then the delay duration is

large. If the consequences are small, then the delay duration is very small." A second estimation of the delay duration was performed using the set of membership functions shown in Table 6.15. The second fuzzy relation can be interpreted as: "If the consequences are large, then the delay duration is large. If the consequences are medium, then the delay duration is medium. If the consequences are small, then the delay duration is small." Table 6.16 summarizes the results of the two duration estimates.

Table 6.14 Membership functions for original duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 4. Smith and Hancher (1989).

	Membership Value		
Duration Elements	**Very Large**	**Large**	**Very Small**
14	0	0	0.9
16	0.2	0.2	0.7
18	0.8	0.9	0.1
20	0.9	0.8	0.0
Adverse Consequences	Large	Medium	Small

Table 6.15 Membership functions for second duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 4

	Membership Value		
Duration Elements	**Large**	**Medium**	**Small**
14	0	0.3	0.3
16	0.8	0.9	0.9
18	0.9	0.9	0.8
20	0.3	0.3	0.0
Adverse Consequences	Large	Medium	Small

Table 6.16 Results of delay duration estimates for Parameter 4

	Mean [days]	Std. Dev. [days]	COV
Original Estimate	18.36	1.54	0.084
Second Estimate	17.08	1.87	0.110

The mean, standard deviation and COV values obtained in the second estimate were compared with respect to that of the original delay duration estimation. Table 6.17 shows the percent deviation obtained.

Table 6.17 Percent deviation in the results of delay duration estimates for Parameter 4

	Mean	Std. Dev.	COV
Second Estimate	-7.51%	17.62%	23.37%

By comparing the percent deviations of the second estimate in Table 6.17, it can be concluded that the delay impact estimation procedure is sensitive to the utilization of a different fuzzy relation between the adverse consequences and the delay duration. By observing the COV values in Table 6.16, it can be concluded that the original estimate is less uncertain than the second duration estimate.

• Parameter 5: Utilization of different delay duration elements in the fuzzy relation between the adverse consequences and the delay duration.

The delay duration was originally determined using the membership functions shown in Table 6.18, defining the linguistic variables that describe the fuzzy relation between the adverse consequences and the delay duration. These membership values are the ones utilized by Smith and Hancher (1989) in their proposed methodology. A second estimation of the delay duration was performed using the set of membership functions shown in Table 6.19. A third estimation of the delay duration was performed using the set of membership functions shown in Table 6.20. Table 6.21 summarizes the results of the two duration estimates.

Table 6.18 Membership functions for original duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 5. Smith and Hancher (1989).

	Membership Value		
Duration Elements	**Very Large**	**Large**	**Very Small**
14	0	0	0.9
16	0.2	0.2	0.7
18	0.8	0.9	0.1
20	0.9	0.8	0.0
Adverse Consequences	Large	Medium	Small

Table 6.19 Membership functions for second duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 5

	Membership Value		
Duration Elements	**Very Large**	**Large**	**Very Small**
16	0	0	0.7
17	0.2	0.8	0.9
18	0.8	0.9	0.1
19	0.9	0.3	0.0
Adverse Consequences	Large	Medium	Small

Table 6.20 Membership functions for third duration estimate for activity Secondary Clarifier Concrete Demolition - Sensitivity to Parameter 5

	Membership Value		
Duration Elements	**Very Large**	**Large**	**Very Small**
12	0	0	0.7
15	0.2	0.8	0.9
18	0.8	0.9	0.1
21	0.9	0.3	0.0
Adverse Consequences	Large	Medium	Small

Table 6.21 Results of delay duration estimates for Parameter 5

	Mean [days]	**Std. Dev.** [days]	**COV**
Original Estimate	18.36	1.54	0.084
Second Estimate	18.18	0.77	0.042
Third Estimate	18.54	2.32	0.125

The mean, standard deviation and COV values obtained in the second and third estimates were compared with respect to that of the original delay duration estimation. Table 6.22 shows the percent deviation obtained.

Table 6.22 Percent deviation in the results of delay duration estimates for Parameter 5

	Mean	Std. Dev.	COV
Second Estimate	-0.99%	50.00%	49.50%
Third Estimate	0.97%	33.34%	32.68%

By comparing the percent deviations of the second estimate in Table 6.22, it can be concluded that the delay impact estimation procedure is sensitive to utilization of different delay durations elements in the fuzzy relation between the adverse consequences and the delay duration. By observing the COV values in Table 6.21, and Tables 6.18 to 6.20, it can be concluded that the uncertainty in the delay duration estimates is related to the extent of the range in the delay duration. The second estimate is the least uncertain estimate, and the extent of its range duration is three days (i.e. 16 to 19 days). The original estimate is the next uncertain estimate, and the extent of its range duration is six days (i.e. 14 to 20). The third estimate is the most uncertain estimate, and the extent of its range duration is nine days (i.e. 12 to 21 days). The uncertainty in the delay duration estimates increases when the range in the delay duration increases.

6.2 Validation of the Procedure for Forecasting Progress at Completion

An analysis was performed in order to compare the results of the procedure for forecasting progress at completion, which makes use of the FNET technique proposed by Lorterapong and Moselhi (1996), with the actual results recorded in the as-built database of the case study project. The snapshot 9 schedule is used to determine the accuracy of the procedure. In this snapshot some activities are experiencing delays and consequently they have fuzzy durations and fuzzy times. Some of their successor activities are being affected by the delays and thus have fuzzy times.

The Snapshot 9 schedule was selected for the analysis because the delays affected activities on the critical path, consequently all activities on this path have fuzzy durations and therefore the project duration is a fuzzy value. The fuzzy duration was used as the starting point in the calculations for the backward pass. This fuzzy value was propagated throughout the schedule, causing all activity durations to become fuzzy. This is also the case of snapshots 10 to 12. The project duration of snapshot 13 is crisp because the delays that affected the critical activities were concluded at this point in time.

The scheduling computations were performed again using the actual delay durations of project activities, which are recorded in the as-built database. Since the values of the delay durations are known, the revised durations are crisp and all the early and finish times in the schedule are also crisp. Table 6.23 shows a comparison between the scheduling results obtained by the procedure for forecasting progress at completion, and the actual results. The values for the early times, late times, and the total float are compared. The comparison is made between the actual values, and the modal values of the fuzzy triangular numbers that represent the fuzzy times. The percent deviations of the fuzzy modal values from the actual values are shown in Table 6.23.

Table 6.23 Actual Results versus the fuzzy scheduling results for snapshot 9

ID	Activity	Early Start			Early Finish			Late Start			Late Finish			Total Float		
		FNET mode	Actual	Percent Deviation	FNET mode	Actual	Percent Deviation	FNET mode	Actual	Percent Deviation	FNET mode	Actual	Percent Deviation	FNET mode	Actual	Percent Deviation
1	Mobilization	0.00	0.00	-	8.00	8.00	-	0.19	0.00	0.00%	8.19	8.00	2.38%	0.19	0.00	0.00%
2	Protection of exterior tanks	1.00	1.00	-	3.00	3.00	-	1.19	1.00	0.00%	3.19	3.00	6.35%	0.19	0.00	0.00%
3	Hoarding Tanks	6.00	6.00	-	68.13	68.00	0.20%	60.06	60.00	0.10%	122.19	122.00	0.16%	54.06	54.00	0.11%
4	M. R. - 100 mm PRA coarse bubble areati	2.00	2.00	-	32.00	32.00	-	2.19	2.00	9.52%	32.19	32.00	0.60%	0.19	0.00	0.00%
5	M. R. - Process Air Headers (400 mm PR	32.00	32.00	-	44.00	44.00	-	32.19	32.00	0.60%	44.19	44.00	0.43%	0.19	0.00	0.00%
6	M. R. - 100 mm PA piping	36.00	36.00	-	79.00	79.00	-	79.19	79.00	0.24%	122.19	122.00	0.16%	44.07	43.00	2.50%
7	Sec. Clarifier Conc. Demolition	7.00	7.00	-	46.00	46.00	-	7.19	7.00	2.72%	46.19	46.00	0.41%	0.19	0.00	0.00%
8	Bioreactor Concrete Demolition	8.00	8.00	-	81.18	81.00	0.22%	8.19	8.00	2.38%	81.37	81.00	0.46%	0.19	0.00	0.00%
9	Sec.Clar. tank fill connections	41.00	41.00	-	45.00	45.00	-	115.19	115.00	0.17%	119.19	119.00	0.16%	75.07	74.00	1.45%
10	SC Temporary bulkheads	34.00	34.00	-	35.00	35.00	-	121.19	121.00	0.16%	122.19	122.00	0.16%	88.07	87.00	1.23%
11	SC Install PW/DRN piping	50.00	50.00	-	53.00	53.00	-	119.19	119.00	0.16%	122.19	122.00	0.16%	70.07	69.00	1.56%
13	Rebar delivery	40.00	40.00	-	40.00	40.00	-	60.19	60.00	0.32%	60.19	60.00	0.32%	20.19	20.00	0.95%
14	Construction of concrete Influent Chamber	85.19	85.00	0.22%	106.19	106.00	0.18%	101.19	101.00	0.19%	122.19	122.00	0.16%	16.00	16.00	0.00%
15	Construction of concrete Influent Pump	60.19	60.00	0.32%	79.19	79.00	0.24%	60.19	60.00	0.32%	79.19	79.00	0.24%	0.00	0.00	0.00%
16	Concrete pipe supports	100.19	100.00	0.19%	122.19	122.00	0.16%	100.19	100.00	0.19%	122.19	122.00	0.16%	0.00	0.00	0.00%
17	Concrete Benching	104.19	104.00	0.18%	108.19	108.00	0.18%	118.19	118.00	0.16%	122.19	122.00	0.16%	14.00	14.00	0.00%
18	Concrete end of y-channel	86.19	86.00	0.22%	120.19	120.00	0.16%	88.19	88.00	0.22%	122.19	122.00	0.16%	2.00	2.00	0.00%
19	Drainage Sump concrete	63.19	63.00	0.30%	74.19	74.00	0.26%	111.19	111.00	0.17%	122.19	122.00	0.16%	48.00	48.00	0.00%
20	Construction of Concrete baffle walls	64.19	64.00	0.30%	91.19	91.00	0.21%	64.19	64.00	0.30%	91.19	91.00	0.21%	0.00	0.00	0.00%
21	Concrete R&P	90.19	90.00	0.21%	114.19	114.00	0.17%	98.19	98.00	0.19%	122.19	122.00	0.16%	8.00	8.00	0.00%
22	Demolition & Concrete galleries	50.00	50.00	-	109.00	109.00	-	63.19	63.00	0.30%	122.19	122.00	0.16%	14.07	13.00	8.26%
23	ML/PE pipe supports delivery	51.00	51.00	-	51.00	51.00	-	74.19	74.00	0.26%	74.19	74.00	0.26%	24.07	23.00	4.67%
24	ML pipe supports install	51.00	51.00	-	65.00	65.00	-	74.19	74.00	0.26%	88.19	88.00	0.22%	24.07	23.00	4.67%
25	PA pipe supp.delivery	71.00	71.00	-	71.00	71.00	-	94.19	94.00	0.20%	94.19	94.00	0.20%	24.07	23.00	4.67%
26	PA pipe supports install	71.00	71.00	-	90.00	90.00	-	94.19	94.00	0.20%	113.19	113.00	0.17%	24.07	23.00	4.67%
27	Delivery of mixers	17.00	17.00	-	17.00	17.00	-	83.19	83.00	0.23%	83.19	83.00	0.23%	66.19	66.00	0.29%
28	Installation of submersible propeller type m	34.00	34.00	-	62.00	62.00	-	83.19	83.00	0.23%	111.19	111.00	0.17%	50.07	49.00	2.19%
29	Aeration system delivery	24.00	24.00	-	24.00	24.00	-	83.19	83.00	0.23%	83.19	83.00	0.23%	60.07	59.00	1.82%
30	Aeration system install	34.00	34.00	-	73.00	73.00	-	83.19	83.00	0.23%	122.19	122.00	0.16%	50.07	49.00	2.19%
31	ML pump delivery	85.00	85.00	-	85.00	85.00	-	116.19	116.00	0.16%	116.19	116.00	0.16%	32.07	31.00	3.46%
32	ML piping delivery	49.00	49.00	-	49.00	49.00	-	49.19	49.00	0.39%	49.19	49.00	0.39%	0.19	0.00	0.00%
33	ML piping install	49.00	49.00	-	100.00	100.00	-	49.19	49.00	0.39%	100.19	100.00	0.19%	0.19	0.00	0.00%
34	ML pump install	86.00	86.00	-	92.00	92.00	-	116.19	116.00	0.16%	122.19	122.00	0.16%	31.07	30.00	3.58%
35	PE piping delivery	50.00	50.00	-	50.00	50.00	-	81.19	81.00	0.24%	81.19	81.00	0.24%	32.07	31.00	3.46%
36	PE piping install	57.00	57.00	-	98.00	98.00	-	81.19	81.00	0.24%	122.19	122.00	0.16%	25.07	24.00	4.47%
37	PE Pump delivery	64.00	64.00	-	64.00	64.00	-	118.19	118.00	0.16%	118.19	118.00	0.16%	55.07	54.00	1.99%
38	PE Pump Install	105.00	105.00	-	109.00	109.00	-	118.19	118.00	0.16%	122.19	122.00	0.16%	14.07	13.00	8.26%
39	PA piping delivery	81.00	81.00	-	81.00	81.00	-	113.19	113.00	0.17%	113.19	113.00	0.17%	33.07	32.00	3.36%
41	PA piping install 1	96.00	96.00	-	105.00	105.00	-	113.19	113.00	0.17%	122.19	122.00	0.16%	18.07	17.00	6.32%

In the case of snapshot 9, the actual project duration obtained is 122 days. The fuzzy project duration obtained using FNET is (120, 122, 125) days. In this case, the fuzzy mode coincides with actual duration. With respect to the fuzzy early and late times, the percent deviations of the fuzzy modal values from the their respective actual values range from 0.16% to 9.52%, with an average of 0.66%. In all the cases, FNET slightly overestimated the values, (i.e. the fuzzy modal values are higher than the actual values). With respect to the total float, the percent deviations of the fuzzy modes from their respective actual values range from 0.11% to 8.26%, with an average of 1.86%. In all the cases, FNET slightly overestimated the total float values.

Consequently, it can be concluded that the performance of the procedure for forecasting progress at completion is acceptable. The results obtained from the FNET method are meaningful and are in close agreement with the actual values observed in the field.

6.3 Summary

This chapter presented a sensitivity analysis to evaluate the sensitivity of the delay impact estimation procedure to membership values in the definition of the linguistic variables. It can be concluded that the delay impact estimation procedure is not sensitive to small variations in the membership values that define the linguistic variables describing the fuzzy relations between the frequency of occurrence and adverse consequences, and between the adverse consequences and the delay duration. This was expected since Ayyub and Haldar (1984) stated that their proposed methodology "is not sensitive to small variation in the membership functions". On the other hand, it can be concluded that the delay impact estimation procedure is sensitive to large variations in the sets of

membership functions, to the choice of fuzzy relation between the adverse consequences and the delay duration, and to the range of the delay duration elements in the fuzzy relation between the adverse consequences and the delay duration. Ayyub and Haldar (1984) stated that the accuracy of their method can be refined with more applications of the technique on various projects.

This chapter also presented a validation analysis to compare the results of the procedure for forecasting progress at completion, which makes use of the FNET technique proposed by Lorterapong and Moselhi (1996), with the actual results recorded in the as-built database of the case study project. It was concluded that the results obtained from the FNET technique are meaningful and are in close agreement with the actual values observed in the field.

CHAPTER 7 CONCLUSIONS AND FUTURE RESEARCH

7.1 Summary and Conclusions

The main objective of this thesis was to develop a fuzzy logic model that integrates the processing of information related to ongoing site work and delays encountered on a daily basis, with an updating and forecasting system. The model assists in the analysis of the subsequent effects that delaying events may have on the completion date of the project. This objective was achieved by developing a fuzzy logic model that has the following features: contains an as-built database for daily site reporting, which is integrated with project scheduling; relates the causes of delays with their corresponding categories; contains a procedure for determining the anticipated duration of delays; updates the schedule in terms of revised activity durations, determines the actual project completion time; identifies which activity delays contribute to the overall project delay; and presents the project manager with the likely consequences of delays on activity progress. The effectiveness of the fuzzy logic model was validated using a case study of an actual project.

The first stage of the research was the development of an as-built database for the case study project. This database was constructed using the information collected, and contains daily project information on activity progress and delays that affected the planned sequence of construction. An as-built schedule was derived for the case study project, and it was compared and analyzed with respect to the as-planned schedule.

Once the practical stage of the research concluded, the second stage was to design a fuzzy logic model dedicated to construction daily site recording and progress forecasting. The first step in the development of the fuzzy logic model was the design of

a general as-built database intended to store daily project information, and to use this information to categorize delays. The purpose of the database within the fuzzy logic model is to integrate daily site reporting with project scheduling. The information stored in the database is interpreted by the fuzzy logic model to update the schedule in terms of actual start and finish dates.

The third stage involved the creation of the lists that contain potential causes of delays, and the development of the cause-effect matrix employed by the fuzzy logic model to categorize delays, by relating the causes of delays with their corresponding responsibility.

The fourth stage of the study dealt with the development of a procedure to estimate the anticipated duration of delays, by means of qualitative assessments about delay-sensitive attributes, frequency of occurrence and adverse consequences regarding the delay, utilizing fuzzy sets and fuzzy relations.

The fifth stage included the implementation of the fuzzy logic technique to transform the PDF that represents the delay duration, into a triangular membership function. The delay duration is transformed by this technique into a triangular fuzzy number, and then the original activity duration is revised and increased using fuzzy addition, in order to account for the occurrence of the delay.

The sixth stage of the research involved the implementation of the fuzzy set theory technique applied to construction network scheduling. This technique recalculates and updates the schedule in terms of revised fuzzy activity durations, in order to determine fuzzy early and late times, and the actual project completion date.

The seventh stage of the research involved the development of a procedure for determining the effects of delays on the schedule by evaluating if the delays have the

effect of altering the project completion date. This stage also included the development of a procedure for assessing the likely consequences of delays on activity progress, such as rescheduling and accelerating project activities. The procedures developed in this stage reflect the dynamic nature of the project schedule and especially the critical path, by determining if the delay that affected a particular activity has the effect of modifying the network logic (i.e. by generating new critical paths or shifting the critical path), and/or if it has the effect of delaying the project completion date. The results of the analysis of these effects are used by the fuzzy logic model to recalculate the schedule based on the measures taken by the user to avoid or mitigate the effects of delays.

The eighth stage of the research involved the validation of the fuzzy logic model developed using the case study project information. The project as-planned information was the initial input to the analysis. The fuzzy logic model sequentially updated the as-planned information each time a delay occurred on a project activity. The input information provided to the fuzzy logic model to update the schedule was the data contained in the as-built database created for the project. This information describes the occurrences of delays and the actual construction sequence. In each snapshot, the decisions of project management with respect to the delaying events were also inputs to the fuzzy logic model. These decisions are related to the measures that project management took in order to deal with the negative impact of delays.

The as-planned schedule provided by the contractor, which was modified during the analysis, and the as-built schedule prepared by the author in the first stage of this research were the starting and finishing points of the analysis. No intermediate update schedules were available from project documentation that could provide insight into project progress between these two points in time. The analysis performed by the fuzzy

logic model created sequential schedule updates of the project that portray precisely how the project evolved from the as-planned schedule to the as-built schedule. The status of project activities was reconstructed by the fuzzy logic model so that each snapshot correctly portrayed the different construction stages. An as-built schedule was obtained by the fuzzy logic model in the last snapshot, which contains the cumulative effects of all the delays that affected the normal progress of project activities.

During the data collection stage of the research, contemporaneous sources of project information were analyzed and processed, and an as-built schedule was derived from the as-built database prepared for the project. It was necessary to develop this as-built schedule because a schedule that showed how the project was actually built, had not been prepared by the contractor of this project. The as-built schedule prepared contains the actual duration of the activities and the logic among them that led to the actual sequence of construction. This as-built schedule was used as a reference point in the analysis, and it was compared to the as-built schedule produced as the final output of the fuzzy logic model. This comparison was done for validation purposes, to evaluate how the results obtained form the fuzzy logic model deviated from the results observed in the field.

The as-built schedule derived by the fuzzy logic model in the last snapshot, coincided with the as-built schedule prepared initially for the project. This indicates that the delay durations predicted by the fuzzy logic model were in close agreement with the delay durations observed on site. This fact also indicates that the fuzzy network scheduling technique used to update the schedule is efficient and produced realistic results. Consequently, the fuzzy logic model proposed in this research is a useful technique that handles the uncertainty associated with predicting the likely consequences

of delaying events, and produces realistic progress forecasts that can be used as a basis for planning remaining work in the schedule.

The last stage of this study involved conducting a sensitivity analysis to evaluate the sensitivity of the delay impact estimation procedure to membership values in the definition of the linguistic variables. It was concluded that the delay impact estimation procedure is not sensitive to small variations in the membership values that define the linguistic variables describing the fuzzy relations between the frequency of occurrence and adverse consequences, and between the adverse consequences and the delay duration. On the other hand, it was concluded that the delay impact estimation procedure is sensitive to large variations in these membership functions, to the choice of fuzzy relation between the adverse consequences and the delay duration, and to the range of the delay duration elements in the fuzzy relation between the adverse consequences and the delay duration.

A validation analysis was also performed to compare the results of the modified FNET procedure for forecasting progress at completion, with the actual results recorded in the as-built database of the case study project. It was concluded that the results obtained from the FNET technique are meaningful and are in close agreement with the actual values observed in the field.

7.2 Contributions

This research has made several contributions that are valuable in the academic research field and in the construction industry. The main contribution of this research is the application of fuzzy logic concepts to the area of construction delay analysis. Most research applications in this area involve the development of computer-based expert

systems for delay analysis. Until now, a fuzzy logic framework has not been applied to construction delay analysis. The introduction of a model based on the techniques of fuzzy logic, provides a flexible and more accurate delay analysis technique that will best suit the imprecise nature associated with predicting the negative effects of construction delays on the schedule.

Another important contribution of this research involves the expansion of previous studies that utilize fuzzy logic techniques applied for project scheduling and planning. (Ayyub and Haldar, 1984; Lorterapong and Mosheli, 1996). This expansion was achieved by creating a bridge that connects these two important approaches, which clearly complement each other. A link was forged between these two techniques by using the outputs produced by the methodology proposed by Ayyub and Haldar (1984) as the inputs of the methodology proposed by Lorterapong and Mosheli (1996). The result is a connection between the technique that estimates activity durations using subjective factors, with the technique that uses trapezoidal distributions to model the uncertainty related to the estimation of activity durations. A contribution has been made to the field of project scheduling and planning by developing a very useful and complete approach for handling the uncertainty inherent to construction scheduling. This technique uses subjective assessments regarding the causes of delays and models the revised activity duration using an accurate representation that reflects the uncertainty of predicting the effects of delays in the schedule.

This expansion was also accomplished by providing a new application to the technique presented by Ayyub and Haldar (1984) to determine activity durations. This application is oriented to the field of delay analysis, and it involves the determination of delay durations utilizing the activity interpretation attributes proposed by Russell and

Fayek (1994). The combined use of these two approaches creates a useful technique that can be used to determine the sensitivity of project activities to different causes of delays. The contribution of this research is based on the enhancement of an existent technique by opening a new field of application, and broadening the original logic of the technique with the inclusion of innovative concepts that create an integral approach to analyze construction delays.

The methodology proposed by Lorterapong and Moselhi (1996) was also expanded by proposing a general set of equations that can be used when the activities have lead or lag relationships. These equations can be used in the fuzzy scheduling calculations. The field of application of this technique was widened by including cases of common occurrence in the construction industry.

The overall contribution of the fuzzy logic model developed in this thesis is to provide project managers with a complete tool that assists in the process of forecasting the extent and the consequences of construction delays, and anticipating their likely effects on the work remaining in the schedule. This tool also alerts project managers of the new conditions in the schedule so that they are able to react and take the correct measures in order to avoid and minimize delays.

An important contribution of this thesis to the construction industry, is that this research outlines the important features and data to capture in an as-built database to establish the impact of delays on the schedule. One of the functions of site staff on a construction project is to keep records of what actually takes place during the construction process. The main source of data for progress records are the daily site reports kept by individual members of the site staff. The daily site reports could be difficult to access for a number or reasons: it can be a time consuming process to obtain

useful information from these records; records are missing sometimes; or, the information required is not available, inaccurate, incomplete or misleading. The main shortcoming is that daily site reports are not integrated with the schedule, and still staff often treat them as independent documents.

Compilation of daily site information into an as-built database is fundamental because it provides the description of the actual status of project activities, provides the causes for deviations from planned schedule, and forges a two-way link between the daily site reporting and planning and scheduling updating.

The fuzzy logic model developed provides industry practitioners with a useful technique for incorporating as-built data into the schedule, assessing the impact of delays on the schedule, and updating the schedule to reflect the consequences of delays and corrective actions taken. The use of fuzzy logic allows them to use linguistic and subjective assessments, which suits their actual practices.

In dealing with construction claims and disputes, an as-built schedule can prove invaluable when problems arise over which delays contributed to the overall project delay, and which party is responsible for the causes that originated the delays. Human memory is highly unreliable and therefore, it is essential to establish and maintain a good record-keeping database that documents activity progress and delays as they occur.

The fuzzy logic model created in this thesis overcomes the shortcomings and limitations that exist in present-day methods used in construction delay analysis to determine the impact of delays upon the project completion date. Present-day delay analysis techniques are limited by a number of problems: they fail to include the dynamic nature of the construction schedule and the critical path on the analysis; they do not incorporate as-built information; they do not analyse the causes of project delays and do

not identify the party responsible for them; and they do not show the reality of what actually occurred on the project, because the results of the analyses may show Inconsistencies in the completion date of project activities when compared to actual as-built information. The technique employed by the model is viable and sound because it ensures an accurate delay analysis by determining the proper categorization of the delay, identifying delay types and analyzing the criticality status of the affected activities. The mechanism to update the schedule using contemporaneous information ensures that whenever delays are incorporated in the analysis, the schedule that is in effect at the time of the delay is used. This is an important feature of the analysis because any changes in the critical path may alter the original schedule logic and have a great impact on the results of the analysis.

7.3 Limitations of the Research

This research has some limitations. One of the main limitations is related to the information required to create an accurate as-built database. The first stage of this research involved the creation of an as-built database for the case study project. Various sources of information were reviewed and analyzed in order to accurately identify the actual progress observed in the field. In some instances, the base information was incomplete, or lacked the adequate level of detail necessary to provide a clear description of the actual progress on site. In this case, assumptions and judgment were required to determine the actual dates and sequences of activities. In some other instances, when delays were identified, the data available concerning the causes that originated the delay were sketchy or incomplete. Subjective interpretation was also required in this case, in order to infer the true picture of the activities affected. The amount of judgement required

to construct an accurate as-built database is a limitation on the quality of the as-built schedule derived from the database. The as-built database should be prepared and updated as the work progresses, in order to avoid the use of subjective judgement to infer the actual progress on site.

A second limitation is related with the sensitivity of the delay impact estimation procedure to the choice of membership values in the definition of the linguistic variables. Ayyub and Haldar (1984) stated that in order to use their proposed technique, a number of membership functions need to be assessed, which may be in some cases difficult. Ayyub and Haldar also stated that the assumptions employed in translating the linguistic variables into fuzzy sets, have a direct influence in the success in incorporating the impact of the factors that affect the activity duration. In the case of this research, these assumptions influence the success in incorporating the impact of the delay-sensitive attributes that determine the delay duration. Ayyub and Haldar concluded that the assistance of experts was required when translating the linguistic variables into fuzzy sets; and that the method needs to be used frequently and compared with the actual impact of the factors on the activity duration, in order to achieve a higher level of success when choosing the appropriate membership values in the definition of the linguistic variables.

A third limitation lies in the fact that the technique developed for determining revised durations does not allow for trapezoidal membership functions (only triangular ones). Consequently, this technique constraints the user into representing an activity duration that falls between two modal values, with a triangular fuzzy number rather than a trapezoidal fuzzy number, which may be a more accurate representation.

7.4 Recommendations for Future Research

The fuzzy logic model developed in this research requires substantial input from the user. In order for this technique to become a valuable tool for the management of construction projects, it needs to be fully automated to deal with tasks which are routine and repetitive, and that are performed more efficiently by a computer. The automation and computerization of the fuzzy logic model is necessary to effectively and efficiently analyze the massive amounts of information that result from daily site recording, and that are necessary to monitor delays and control the progress of the many interrelated activities that comprise a construction project.

The size of the case study project analyzed in this thesis can be considered relatively small (i.e. 40 activities) compared to much complex projects which may contain hundreds of activities. The duration of this project can also be considered small (i.e. 131 days) when compared to much longer projects which may take various years to complete. The volume of the information processed during the analysis of the case study was fairly large, and the calculations involved an high computational effort. If the fuzzy logic model is used to analyze large and complex construction projects, this would involve complicated and time-consuming calculations for anticipating delay durations and determining the schedule early and finish times. In these cases, it would be almost unfeasible to perform the scheduling calculations, unless the fuzzy logic model is properly automated.

In the case of large and complex construction projects, project managers must determine the number of snapshots used in the analysis, accordingly to the duration of the construction project. The amount of information, calculations and results increases with the number of snapshots, for this reason an adequate number of snapshots is

required to maintain the balance between the accuracy of the analysis and the volume of information processed.

The fuzzy logic developed in this thesis is partially computerized, but there is no link between individual components. Intervention from the user is required to provide this link. The as-built database is implemented in MS Excel, but ideally it should be implemented into a database management software. The delay impact estimation procedure is implemented in MS Excel and MS Visual Basic, but the user must manually input the information. Ideally the database software should be linked with the programming software in order to provide the inputs of the delay impact estimation procedure. The outputs produced by this procedure, the PDF that represents the delay duration, must be entered manually by the user into the procedure that transforms PDF's into membership functions. This procedure is implemented in MS Excel, as well as the procedure to determine revised activity durations. The user must also provide the link between these two procedures. The procedure for forecasting progress at completion is also implemented in MS Excel, and ideally it should be implemented in a project management software. The user must manually enter activity durations and must recalculate the schedule whenever needed. This process should be automated. The procedure to determine the effects of delays on the schedule is also implemented in MS Excel, and the user must analyze the output of this procedure, in order to establish the inputs of the procedure that determines the consequences of delays in the schedule. The user must decide whether it is needed to accelerate or reschedule project activities in order to avoid the effects of delays. Ideally this decision process could be aided by a knowledge-based expert system (KBES).

The technique developed in the fuzzy logic model could also be incorporated into a knowledge-based expert system (KBES), in order to become an integral computer-based aid for project management. Developing a KBES that makes use of fuzzy logic concepts, would be an important contribution to the field of construction delay analysis. The KBES can be focused towards analyzing disputes that arise due to different categories of delays (excusable compensable, excusable non-compensable, and non-excusable), and determining the responsibility of each party. The domain of the knowledge base should contain knowledge related to delay disputes and claim analysis, legal contracts, and the applicable legislation.

A set of expert rules to interpret the model's output could also be useful in guiding the user to identify which activities contribute to the overall project delay and in which manner these delays affect the schedule. The set of expert rules would be used in assessing the combined effect of the factors that determine if a delay is critical to the completion date of the project.

The automation of the fuzzy logic model should involve the creation of an integrated system that links the KBES with a project network scheduling software, and a database management software. The capability to link with these software packages is important in order to exchange, import and export data among the different components of the integrated system.

The purpose of the fuzzy logic model developed in this thesis is to analyze the effects of delaying events on the schedule. Whenever delays affect the normal progress of an activity, the fuzzy logic model determines the duration of the delay and increases the original activity duration by the amount of the delay. During the construction of a project, the project manager may note that some factors may influence the original

duration of an activity, and may have the effect of decreasing its original duration. In this case the project manager may be aware that the duration of the activity will less than he or she expected, but he or she might not be able to forecast the precise duration of the accelerated activity. In this case, the approach to determine delay durations could be used to anticipate the duration of accelerated activities. The framework of the technique can be employed to solve this situation, with the incorporation of a list attributes that determine the sensitivity of an activity to acceleration. The analysis and compilation of such list of attributes is a subject that can be addressed in a future research.

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APPENDIX A CASE STUDY: EXAMPLE HOUSING PROJECT

A.1 Introduction

The following hypothetical project is used to illustrate the concepts presented in Chapter 3. Figure A.1 shows the as-planned bar chart schedule from a house construction project. Figure A.2 shows the schedule translated into a network diagram. The facts relevant to project delays that occurred are given in Table A.1. Figure A.3 shows the cause/effect matrix used to categorize the delays.

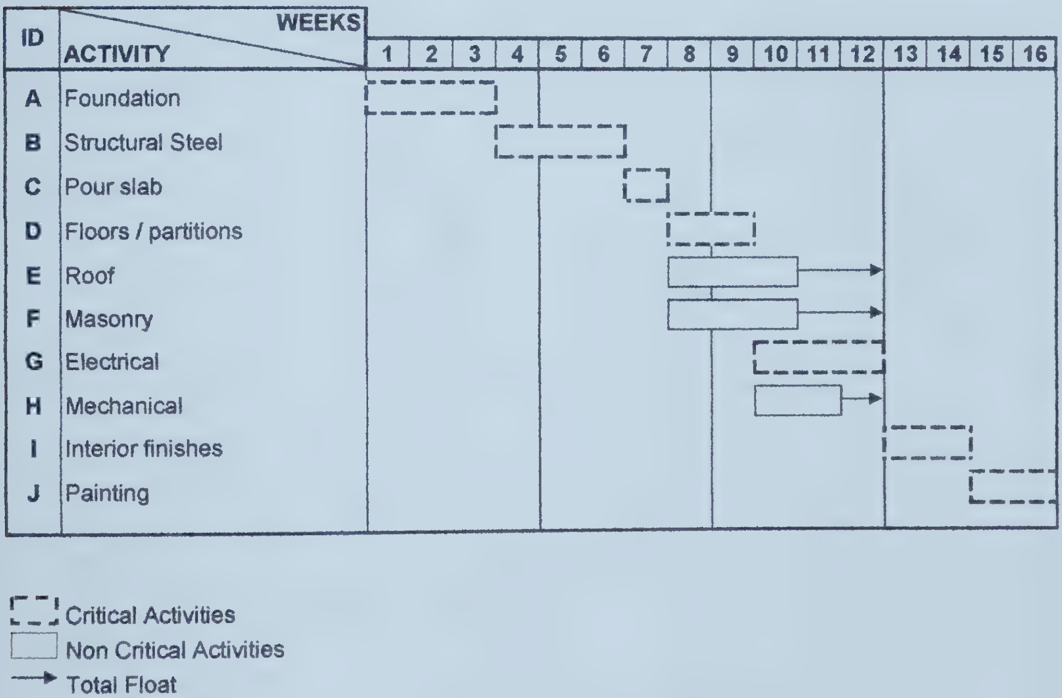

Figure A.1 As Planned Bar Chart Schedule for Example Project

ID	ACTIVITY	Duration Weeks	Earliest		Latest		Total Float
			Start	Finish	Start	Finish	
A	Foundation	3	0	3	0	3	0
B	Structural Steel	3	3	6	3	6	0
C	Pour slab	1	6	7	6	7	0
D	Floors / partitions	2	7	9	7	9	0
E	Roof	3	7	10	9	12	2
F	Masonry	3	7	10	9	12	2
G	Electrical	3	9	12	9	12	0
H	Mechanical	2	8	11	10	12	1
I	Interior finishes	2	12	14	12	14	0
J	Painting	2	14	16	14	18	0

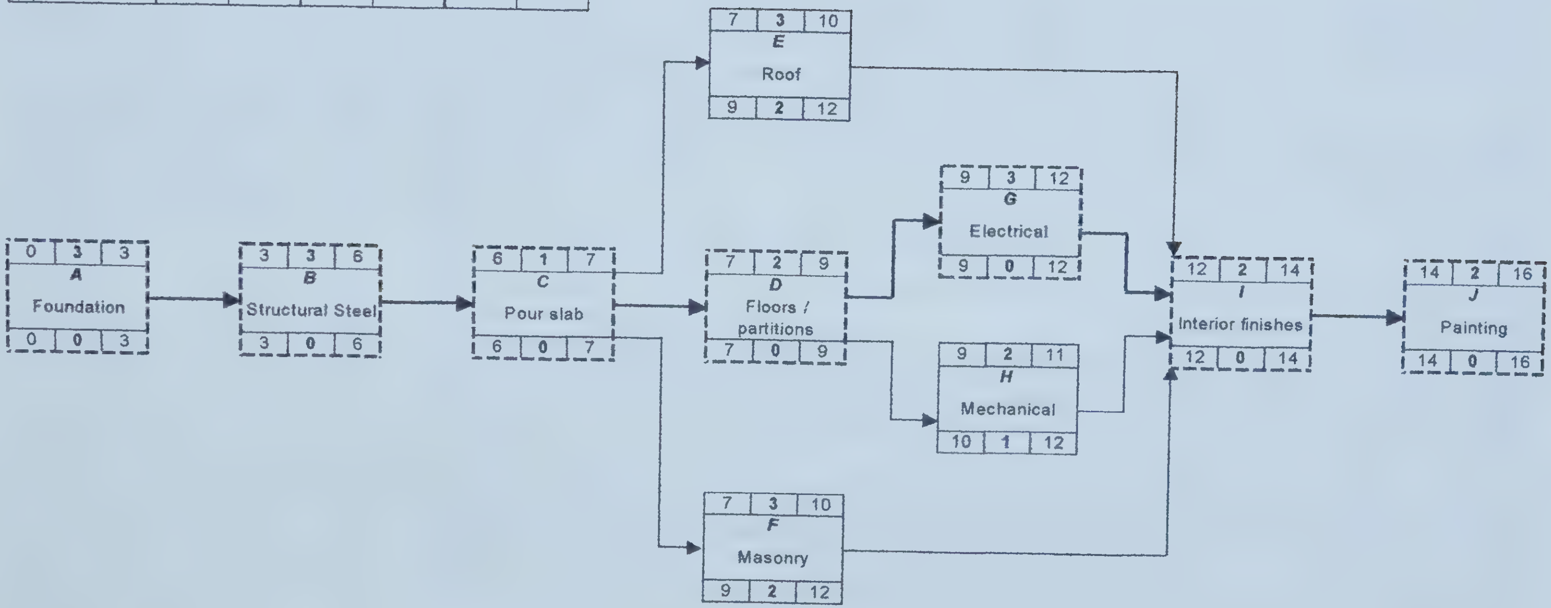

Figure A.2 As Planned Network Diagram Schedule for Example Project

Table A.1 Delays Occurring on Example Project

ID	Activity	Original Duration Weeks	Delay Type	Description of Delays
A	Foundation	3	Type 2	Although the foundation work was scheduled to begin by the beginning of week 1, it did not commence until week 2 because the owner failed to turn over the site on time.
			Type 3	The contractor encountered unforeseen rock at the start of week 3 while excavating the foundation. Work was suspended for one week while the owner's architect conducted tests and redesigned the work.
			Type 3	The aggregate time for performance of the foundation work was 4 weeks rather than the 3 weeks intended. Excavating the foundation proceeded more slowly due to the differing soil conditions.
B	Structural Steel	3	Type 2	The structural steel work began one week later than it was scheduled. The start of the activity was delayed because the owner's architect delayed in approving the structural steel shop drawings.
C	Pour slab	1	Type 1	Start delay due to preceding delay to Structural Steel. Completed within duration originally planned.
D	Floors / partitions	2	Type 3	The progress of the activity was interrupted because the owner decided he did not like the windows called for in the original design.
E	Roof	3	Type 3	Originally, the roofing work was to be performed during good weather. However, it actually had to be performed in the middle of winter, and consequently extended the duration of the works.
			Type 3	Defects were found in the roofing work by the owner's architect, and the contractor had to repair them once he completed the remaining work.
F	Masonry	3	Type 1	Start delay due to preceding delay to Pour Slab. Completed within duration originally planned.
G	Electrical	3	Type 2	The start of the activity was delayed because the building needed to be wind and watertight, so that the roof needed to be completed before the electrical conduits could be commenced. This constraint arose due to the unplanned work during winter.
H	Mechanical	2	Type 2	Delay due to change order issued by the owner's architect to modify the type of equipment to be installed.
			Type 3	The equipment supplier failed to deliver the equipment on time. Work progress was interrupted because the necesary equipment was not on site.
I	Interior finishes	2	Type 1	Start delay due to preceding delay to Roofing, Masonry, Electrical and Mechanical works. Completed within duration originally planned.
J	Painting	2	Type 1	Start delay due to preceding delay to Interior finishes. Completed within duration originally planned.

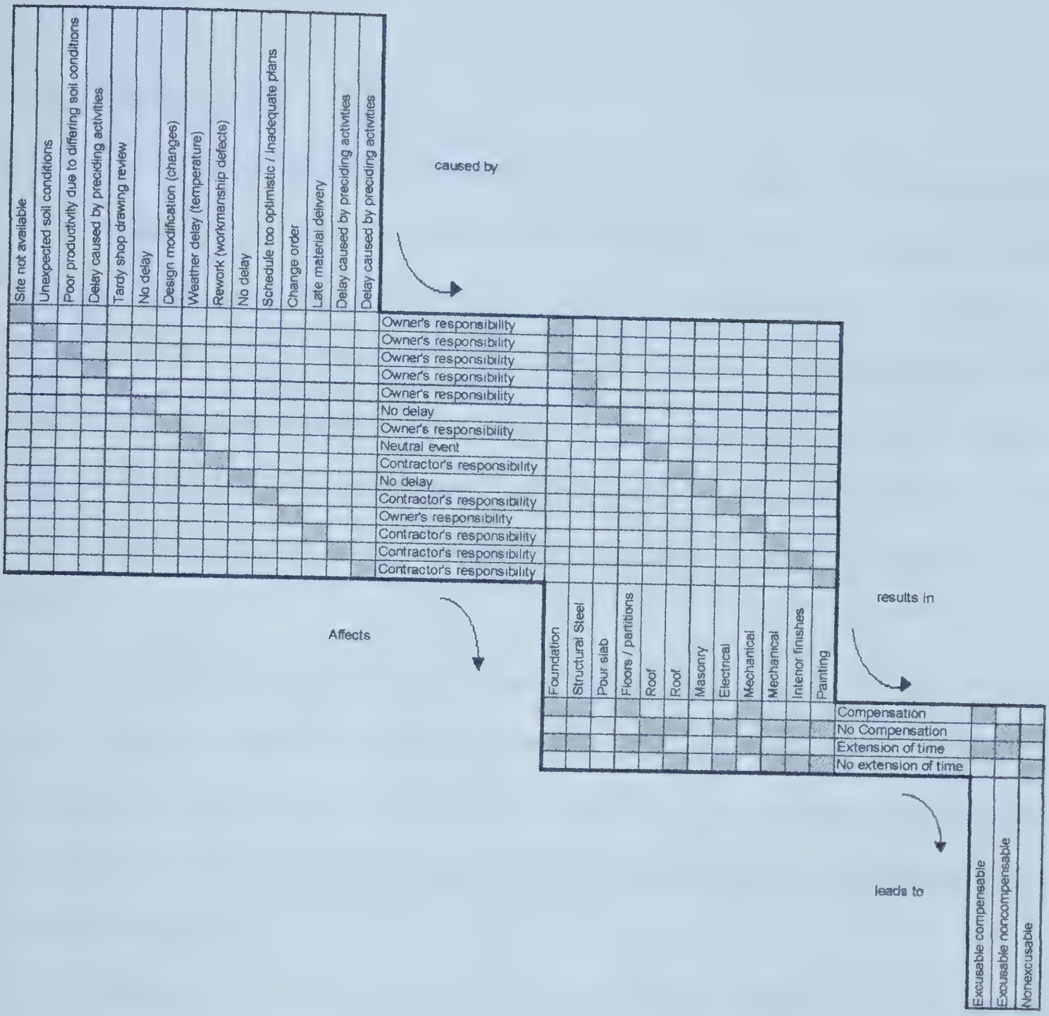

Figure A.3 Delay Categorization Matrix for Example Project

A.2 Analysis of Example Project

A.2.1 First Snapshot

The first snapshot was performed at the beginning of week 11, in order to update the schedule due to a number of delays that occurred during previous weeks. As can be observed on the bar chart corresponding to the first snapshot (Figure A.4), activities, A "Foundation" and, B "Structural", suffered a series of delays. The circumstances that caused these delays are described in Table A.1. The categorization of these delays is shown in Figure A.3. Since the date of the snapshot is subsequent to the dates of the occurrence of delays, all delay durations are known with certainty and thus are crisp values.

The values of delay durations are shown in Table A.21 (Section A.3), and they are used to revise the activity durations (Figure A.6). The network diagram in Figure A.5 incorporates actual durations. Table A.2 and Figure A.7 indicate the effects of delays in the schedule. The as-built database records corresponding to the first snapshot are included in Appendix A.

Activities A "Foundation" and, B "Structural", were critical in the as-planned schedule and the delays they suffered in the first snapshot delayed the project completion time. The critical path remains the same as that of the as-planned schedule. The as-planned project completion time was 16 weeks, and after 10 weeks of progress the actual project completion time is 20 weeks.

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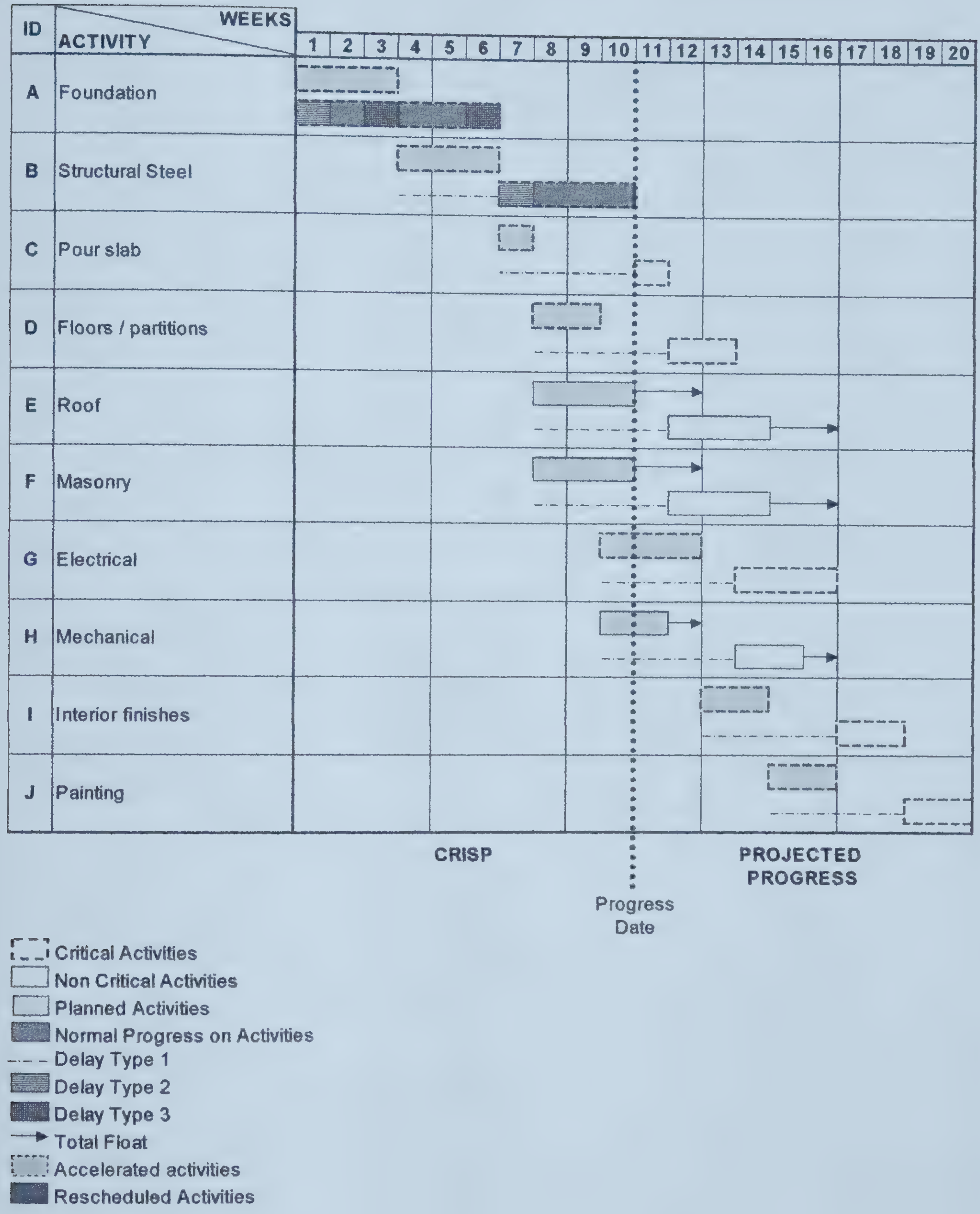


Figure A.4 Bar Chart Schedule - First Snapshot

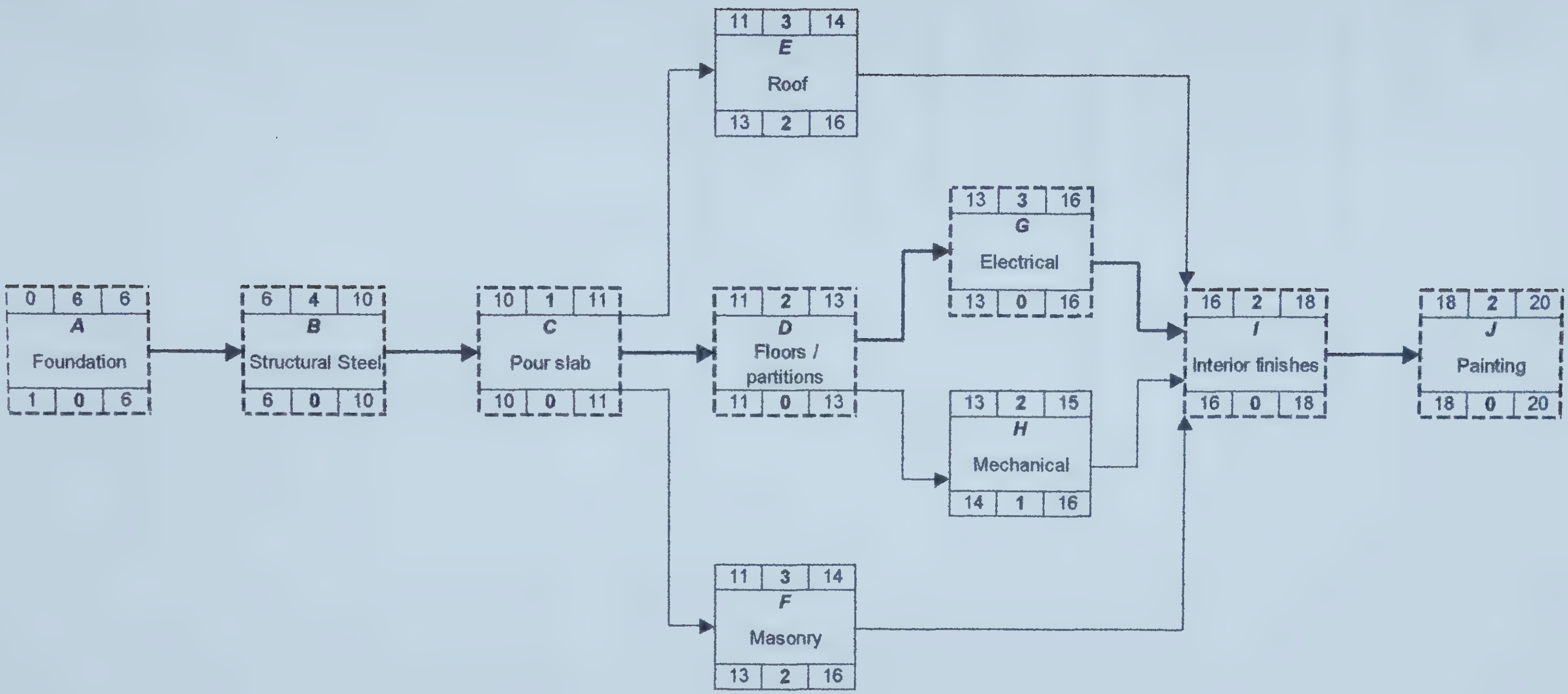


Figure A.5 Network Diagram Schedule - First Snapshot

Activity:

A Foundation

Original duration:	**3**	**weeks**
- Delay Type 2 :	1	week
- Normal Progress:	1	week
- Delay Type 3 :	1	week
- Normal Progress:	2	weeks
- Delay Type 3 :	1	week
Revised duration:	**6**	**weeks**

Activity:

B Structural Steel

Original duration:	**3**	**weeks**
Delay Type 2 :	1	week
Normal Progress:	3	weeks
Revised duration:	**4**	**weeks**

Figure A.6 Revised Activity Durations - First Snapshot

ID	Activity	Original Duration Weeks	Actual Duration Weeks	Type of Delay	Effect of delays on the progress of the works
A	Foundation	3	5	Type 2 Type 3 Type 3	Foundation is a critical activity and it suffered a sequencial combination of delays Type 2 and 3 that has the effect of delaying the project completion date. Activity Foundation remains being critical to the progress of the work after suffering the delays.
B	Structural Steel	3	4	Type 1 Type 2	Structural Steel is a critical activity and it suffered a a sequencial combination of delays Type 1 and 2 that has the effect of delaying the project completion date. Activity Structural Steel remains critical to the progress of the work after suffering the delay.
C	Pour slab	1	1	Type 1	Pour slab is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Pour slab remains critical to the progress of the work after suffering the delay.
D	Floors / partitions	2	2	Type 1	Floors / partitions is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Floors / partitions remains critical to the progress of the work after suffering the delay.
E	Roof	3	3	Type 1	Roof is a non-critical activity and it suffered a delay Type 1 that has no effect upon the completion of the works due to the float that it has with respect to activity Electrical . Activity Roof remains non-critical to the progress of the work after suffering the delay.
F	Masonry	3	3	Type 1	Masonry is a non-critical activity and it suffered a delay Type 1 that has no effect upon the completion of the works due to the float that it has with respect to activity Electrical . Activity Masonry remains non-critical to the progress of the work after suffering the delay.
G	Electrical	3	3	Type 1	Electrical is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Electrical remains critical to the progress of the work after suffering the delay.
H	Mechanical	2	2	Type 1	Mechanical is a non-critical activity and it suffered a delay Type 1 that has no effect upon the completion of the works due to the float that it has with respect to activity Electrical . Activity Mechanical remains non-critical to the progress of the work after suffering the delay.
I	Interior finishes	2	2	Type 1	Interior finishes is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Interior finishes remains critical to the progress of the work after suffering the delay.
J	Painting	2	2	Type 1	Painting is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Painting remains critical to the progress of the work after suffering the delay.

Table A.2 Effects of Delays on the Schedule - First Snapshot

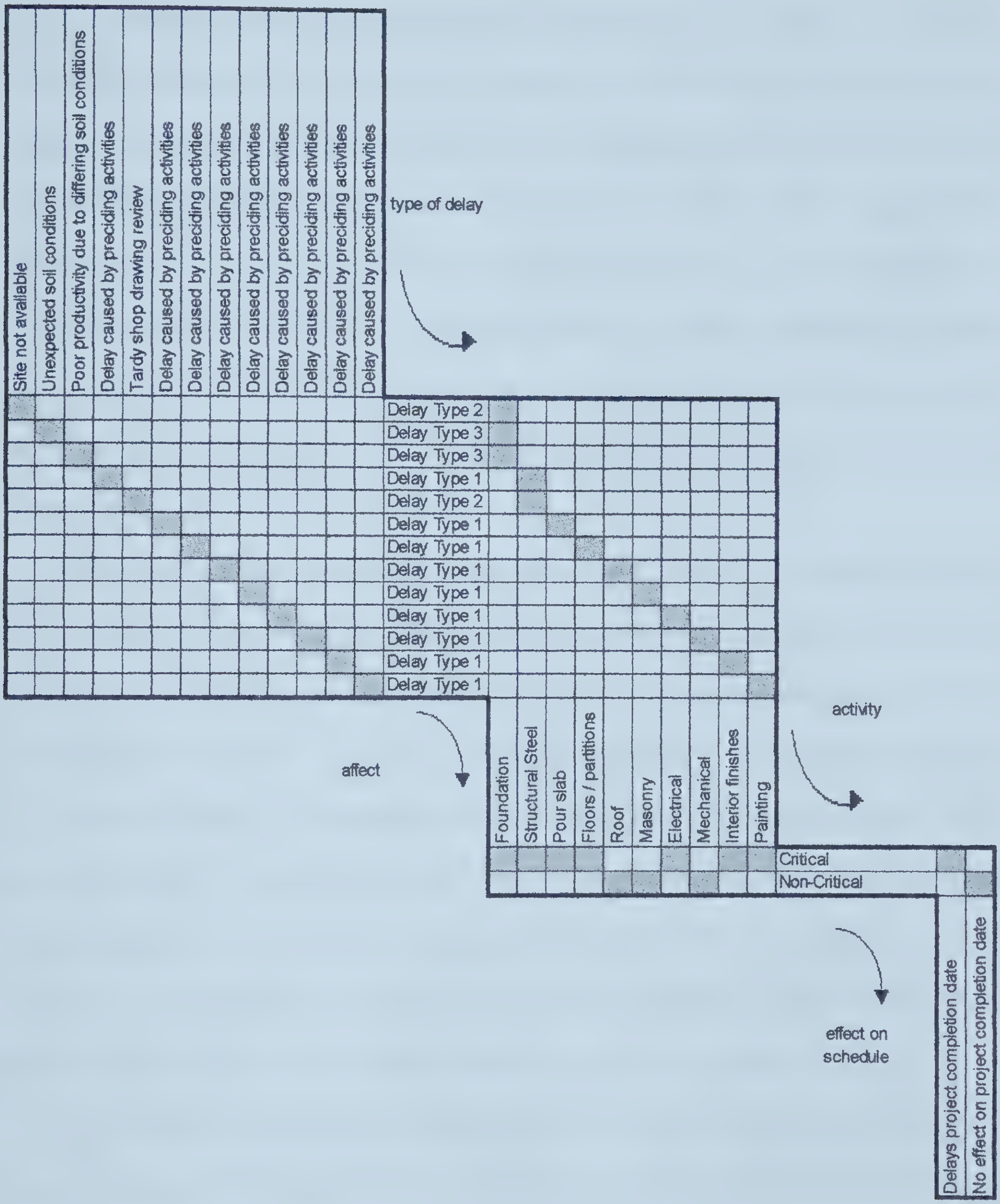


Figure A.7 Cause-Effect Matrix - Effects of Delays on the Schedule - First Snapshot

A.2.2 Second Snapshot

The second snapshot was performed at the beginning of week 13, in order to update the schedule due to a number of delays that occurred during the two previous weeks. As can be observed on the bar chart corresponding to the second snapshot (Figure A.8), activities D, "Floor and Partitions" and E, "Roof", suffered delays. The circumstances that caused these delays are described in Table A.1. The categorization of these delays is shown in Figure A.3. Since the date of the second snapshot corresponds to the date of the occurrence of delays, delay durations are not known with certainty and thus are determined by means of the delay impact estimation procedure, described in Chapter 3.

The fuzzy values of delay durations are shown in Table A.21 (Section A.3), and they are used to revise the activity durations (Figure A.10). The fuzzy network diagram in Figure A.9 incorporates actual durations. The calculations for fuzzy early and finish times are included in Figure A.11. Figure A.12 displays graphically project duration and critical path times and shows the respective criticality measurements. As can be seen in this figure, critical path 1 is the most critical path in the project because it has the largest values of PM and AI. Figure A.13 contains the degree of criticality of activities. Table A.3 and Figure A.14 indicate the effects of delays in the schedule. The as-built database records corresponding to the second snapshot are included in Appendix B.

Activity E, "Roof", was non-critical in the first snapshot schedule, however the delay it suffered in the second snapshot caused it to become critical, thus delaying the project completion time. On the contrary, activity D, "Floor and Partitions" that was critical in the first snapshot schedule became non-critical in the second snapshot even though it suffered a delay, because of the float created by the concurrent delay in activity E, "Roof".

[illegible]

[illegible]

[illegible]

Activity G, "Electrical" also became non-critical in the second shapshot for to the same reason. The critical path shifted from activities A-B-C-D-G-I-J to A-B-C-E-I-J. The project completion time in the first snapshot was 20 weeks, and after 12 weeks of progress the actual project completion time is approximately 22.25 weeks, with a definitive minimum time of 19.44 weeks and a definitive maximum completion time of 25.06 weeks.

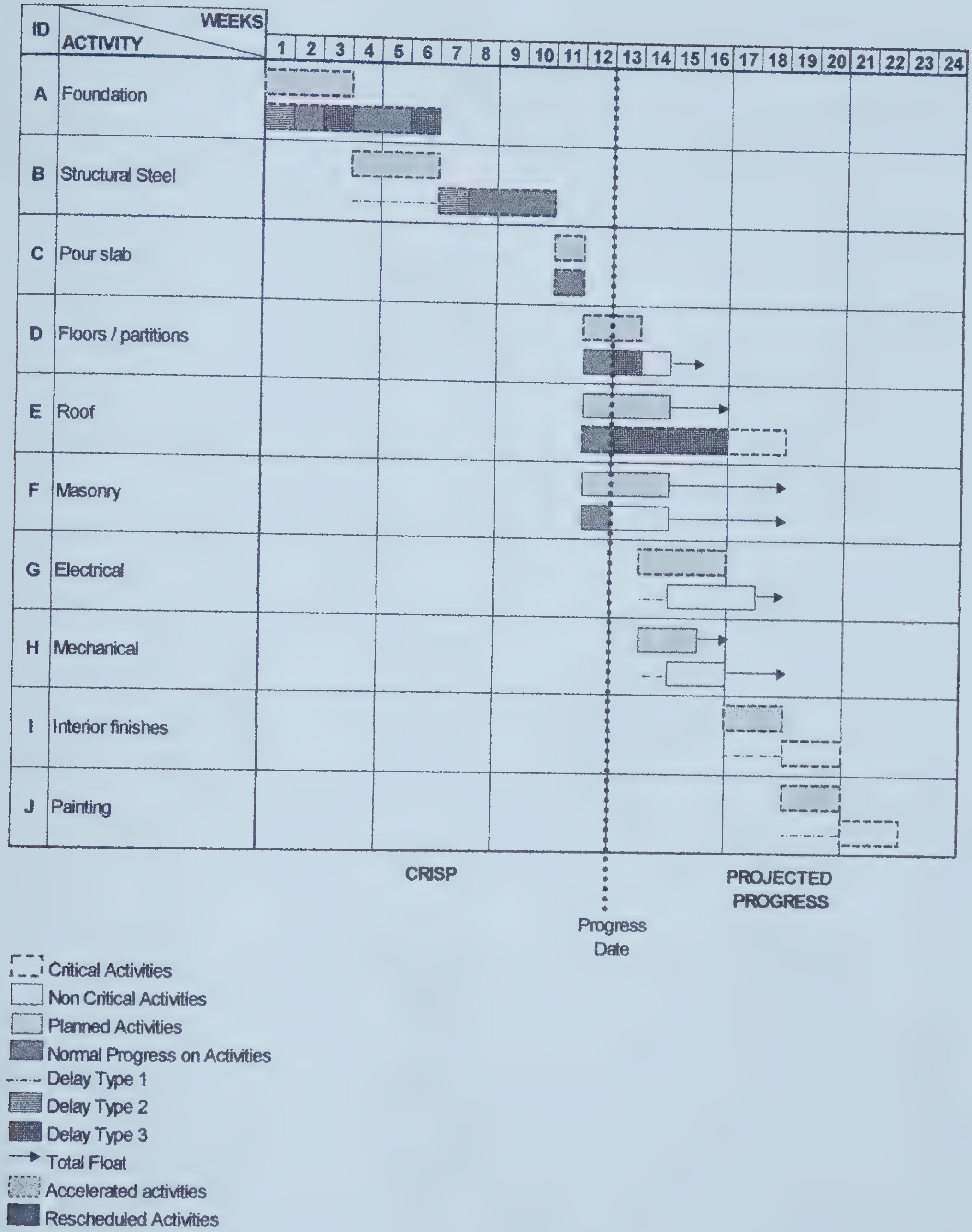


Figure A.8 Bar Chart Schedule - Second Snapshot

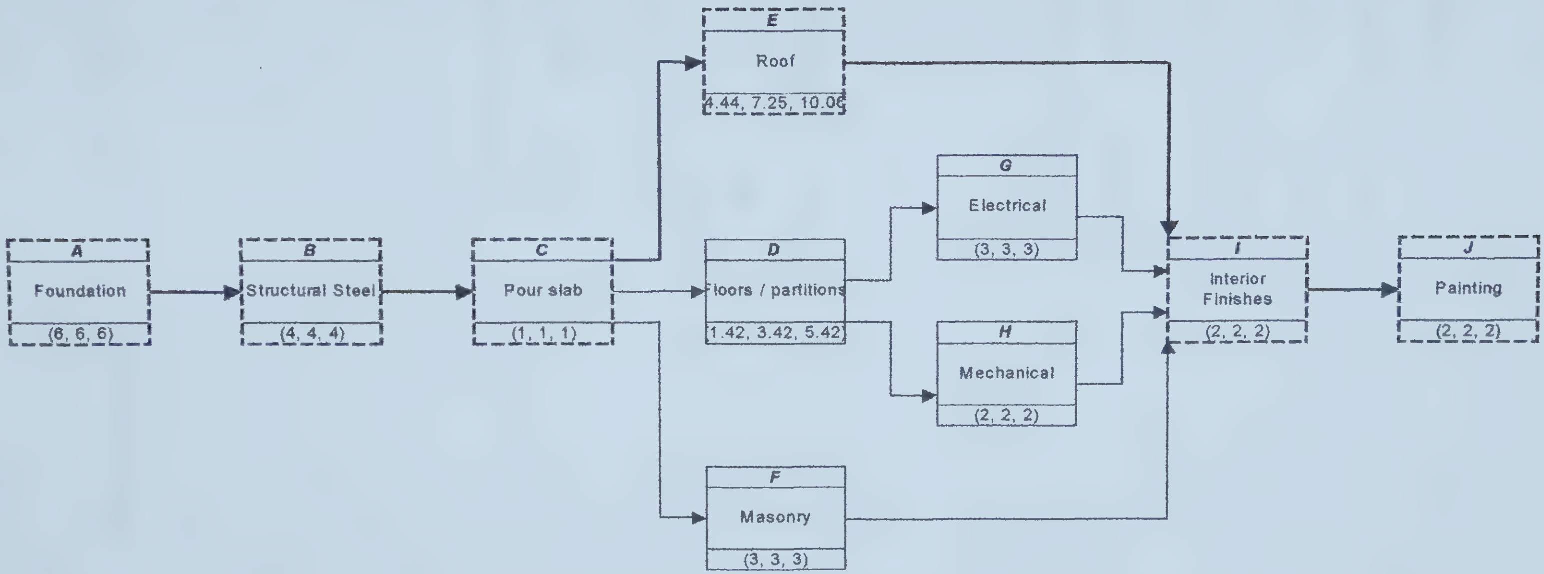


Figure A.9 Network Diagram Schedule - Second Snapshot

Activity:

D Floors / partitions

			Triangular Fuzzy Numbers
Original duration:	**2**	**weeks**	
Normal Progress:	1	week	(1 , 1 , 1)
			$\oplus$
	Mean / Variance		
Delay Type 3 :	1.42 / 0.59	weeks	(-0.58 , 1.42 , 3.42)
			$\oplus$
Remaining duration:	1	week	(1 , 1 , 1)
Revised duration in weeks:			**(1.42 , 3.42 , 5.42)**

Activity:

E Roof

			Triangular Fuzzy Numbers
Original duration:	**3**	**weeks**	
Normal Progress:	1	week	(1 , 1 , 1)
			$\oplus$
	Mean / Variance		
Delay Type 3 (1st) :	4.25 / 0.84		(1.44 , 4.25 , 7.06)
			$\oplus$
Remaining duration:	2	weeks	(2 , 2 , 2)
Revised duration in weeks:			**(4.44 , 7.25 , 10.06)**

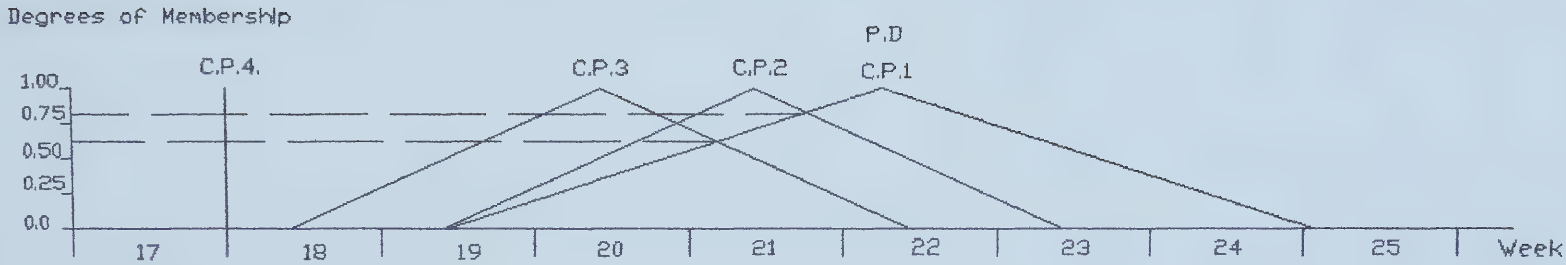
Figure A.10 Revised Activity Durations - Second Snapshot

ID	Activity	Fuzzy Duration	Fuzzy Early Start	Fuzzy Early Finish	Fuzzy Late Start	Fuzzy Late Finish	Total Float
A	Foundation	(6.00 , 6.00 , 6.00 , 6.00)	(0.00 , 0.00 , 0.00 , 0.00)	(6.00 , 6.00 , 6.00 , 6.00)	(0.00 , 0.00 , 0.00 , 0.00)	(6.00 , 6.00 , 6.00 , 6.00)	0.00
B	Structural Steel	(4.00 , 4.00 , 4.00 , 4.00)	(6.00 , 6.00 , 6.00 , 6.00)	(10.00 , 10.00 , 10.00 , 10.00)	(6.00 , 6.00 , 6.00 , 6.00)	(10.00 , 10.00 , 10.00 , 10.00)	0.00
C	Pour slab	(1.00 , 1.00 , 1.00 , 1.00)	(10.00 , 10.00 , 10.00 , 10.00)	(11.00 , 11.00 , 11.00 , 11.00)	(10.00 , 10.00 , 10.00 , 10.00)	(11.00 , 11.00 , 11.00 , 11.00)	0.00
D	Floors / partitions	(1.42 , 3.42 , 3.42 , 5.42)	(11.00 , 11.00 , 11.00 , 11.00)	(12.42 , 14.42 , 14.42 , 16.42)	(12.64 , 12.64 , 12.64 , 12.64)	(14.06 , 16.06 , 16.06 , 18.06)	1.64
E	Roof	(4.44 , 7.25 , 7.25 , 10.06)	(11.00 , 11.00 , 11.00 , 11.00)	(15.44 , 18.25 , 18.25 , 21.06)	(11.00 , 11.00 , 11.00 , 11.00)	(15.44 , 18.25 , 18.25 , 21.06)	0.00
F	Masonry	(3.00 , 3.00 , 3.00 , 3.00)	(11.00 , 11.00 , 11.00 , 11.00)	(14.00 , 14.00 , 14.00 , 14.00)	(15.25 , 15.25 , 15.25 , 18.06)	(18.25 , 18.25 , 18.25 , 21.06)	5.19
G	Electrical	(3.00 , 3.00 , 3.00 , 3.00)	(12.42 , 14.42 , 14.42 , 16.42)	(15.42 , 17.42 , 17.42 , 19.42)	(13.25 , 15.25 , 15.25 , 18.06)	(16.25 , 18.25 , 18.25 , 21.06)	1.10
H	Mechanical	(2.00 , 2.00 , 2.00 , 2.00)	(12.42 , 14.42 , 14.42 , 16.42)	(14.42 , 16.42 , 16.42 , 18.42)	(14.25 , 16.25 , 16.25 , 19.06)	(16.25 , 18.25 , 18.25 , 21.06)	2.10
I	Interior finishes	(2.00 , 2.00 , 2.00 , 2.00)	(15.44 , 18.25 , 18.25 , 21.06)	(17.44 , 20.25 , 20.25 , 23.06)	(15.44 , 18.25 , 18.25 , 21.06)	(17.44 , 20.25 , 20.25 , 23.06)	0.00
J	Painting	(2.00 , 2.00 , 2.00 , 2.00)	(17.44 , 20.25 , 20.25 , 23.06)	(19.44 , 22.25 , 22.25 , 25.06)	(17.44 , 20.25 , 20.25 , 23.06)	(19.44 , 22.25 , 22.25 , 25.06)	0.00

CRITICAL PATH DURATIONS:

1	A-B-C-E-I-J	(19.44 , 22.25 , 22.25 , 25.06)
2	A-B-C-D-G-I-J	(19.42 , 21.42 , 21.42 , 23.42)
3	A-B-C-D-H-I-J	(18.42 , 20.42 , 20.42 , 22.42)
4	A-B-C-F-I-J	(18.00 , 18.00 , 18.00 , 18.00)

Figure A.11 Fuzzy Schedule - Second Snapshot



Critical Paths:

C.P.1=A-B-C-E-I-J
C.P.2=A-B-C-D-G-I-J
C.P.3=A-B-C-D-H-I-J
C.P.4=A-B-C-F-I-J

Possibility Measure and Agreement Index:

PM1=1.00	AI1=1.00
PM2=0.84	AI2=0.72
PM3=0.65	AI3=0.54

Figure A.12 Project Duration and Critical Paths - Second Snapshot

ID	Activity	PM	ΣPM	AI	ΣAI
A	Foundation	1.00	2.09	1.00	2.26
B	Structural Steel	1.00	2.09	1.00	2.26
C	Pour slab	1.00	2.09	1.00	2.26
D	Floors / partitions	0.65	1.09	0.72	1.26
E	Roof	1.00	1.00	1.00	1.00
F	Masonry	0.00	0.00	0.00	0.00
G	Electrical	0.65	0.65	0.72	0.72
H	Mechanical	0.44	0.44	0.54	0.54
I	Interior finishes	1.00	2.09	1.00	2.26
J	Painting	1.00	2.09	1.00	2.26

Figure A.13 Criticality of Activities - Second Snapshot

ID	Activity	Original Duration Weeks	Actual Duration Weeks	Type of Delay	Effect of delays on the progress of the workss
A	Foundation	3	5	Type 1 Type 3 Type 3	Foundation is a critical activity and it suffered a sequencial combination of delays Type 2 and 3 that has the effect of delaying the project completion date. Activity Foundation remains being critical to the progress of the works after suffering the delays.
B	Structural Steel	3	4	Type 1 Type 2	Structural Steel is a critical activity and it suffered a a sequencial combination of delays Type 1 and 2 that has the effect of delaying the project completion date. Activity Structural Steel remains critical to the progress of the work after
C	Pour slab	1	1	-	Work progess on activity Pour Slab proceded as planned with respect to the actual planned schedule.
D	Floors / partitions	2	1.42 Lower Bound; 3.42 Mean; 5.42 Upper Bound	Type 3	Floors / partitions was previously a critical activity and it suffered a delay Type 3 that has no effect upon the completion of the works due to the float that it has with respect to activity Roof . Activity Floors / partitions turned non-critical to the progress of the works even though it suffered delay.
E	Roof	3	4.44 Lower Bound; 7.25 Mean; 10.06 Upper Bound	Type 3	Roof was previously a non-critical activity and it suffered a delay Type 3 that that has the effect of delaying the project completion date. Activity Roof turned critical to the progress of the works after sufering the delay.
F	Masonry	3	3	-	Work progess on activity Masonry is proceding as planned with respect to the actual planned schedule.
G	Electrical	3	3	Type 1	Electrical was previously a critical activity and it suffered a delay Type 1 that has no effect upon the completion of the works due to the float that it has with respect to activity Roof. Activity Electrical turned non-critical to the progress of the works even though it suffered delay.
H	Mechanical	2	2	Type 1	Mechanical is a non-critical activity and it suffered a delay Type 1 that has no effect upon the completion of the works due to the float that it has with respect to activity Electrical . Activity Mechanical remains non-critical to the progress of the work after suffering the delay.
I	Interior finishes	2	2	Type 1	Interior finishes is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Interior finishes remains critical to the progress of the works after suffering the delay.
J	Painting	2	2	Type 1	Painting is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Painting remains critical to the progress of the works after suffering the delay.

Table A.3 Effects of Delays on the Schedule - Second Snapshot

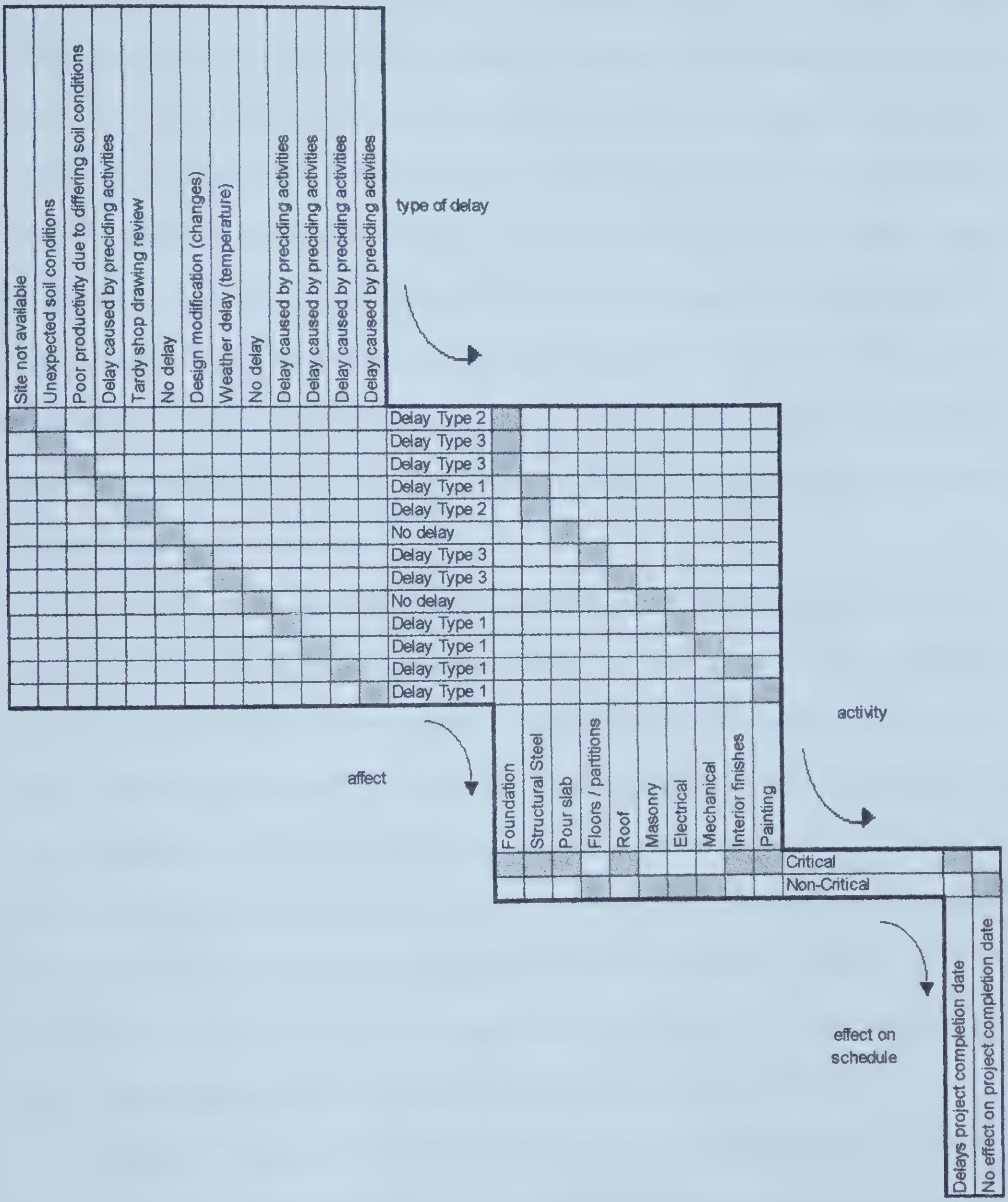


Figure A.14 Cause-Effect Matrix - Effects of Delays on the Schedule - Second Snapshot

[illegible]

A.2.3 Third Snapshot

The third snapshot was performed at the beginning of week 15, in order to update the schedule due to a number of delays that occurred during the previous two weeks. As can be observed on the bar chart corresponding to the third snapshot (Figure A.15), activities G, "Electrical" and H, "Mechanical" suffered delays, and it was determined that activity E, "Roof" will suffer a second delay. The circumstances that caused these delays are described in Table A.1. The categorization of these delays is shown in Figure A.3. Since the date of the snapshot corresponds to the date of the occurrence of delays or is previous (in the case of activities E, "Roof" and H, "Mechanical"), delay durations are not known with certainty and thus are determined by means of the delay impact estimation procedure, described in Chapter 3.

The fuzzy values of delay durations are shown in Table A.21 (Section A.3) and they are used to revise the activity durations (Figure A.17). The fuzzy network diagram in Figure A.16 incorporates actual durations. The calculations for fuzzy early and finish times are included in Figure A.18. Figure A.19 displays graphically project duration and critical path times and shows the respective criticality measurements. As can be seen in this figure, critical path 3 is the most critical path in the project because it has the largest values of PM and AI. Figure A.20 contains the degree of criticality of activities. Table A.4 and Figure A.21 indicate the effects of delays on the schedule. The as-built database records corresponding to the third snapshot are included on Appendix C.

Activity H, "Mechanical" was non-critical in the second snapshot schedule, and the two delays it suffered in the third snapshot caused it to become critical thus delaying the project completion time. On the contrary, activity E, "Roof" that was critical in the second snapshot schedule, became non-critical in the third snapshot even though it is

suffering from a delay and it is anticipated that it will suffer a second delay, later. This change in the criticality status of activity E, "Roof" was created because of the float created by the concurrent delay in activity H, "Mechanical". Activity G, "Electrical" remained non-critical in the third snapshot due to the same reason, even though it also experienced a delay. The critical path shifted once again from activities A-B-C-E-I-J to A-B-C-D-H-I-J. The project completion time on the second snapshot was (19.44, 22.25, 25.06) weeks, and after 14 weeks of progress the actual project completion time is approximately 28.95 weeks, with a definitive minimum time of 24.88 weeks and a definitive maximum completion time of 33.02 weeks.

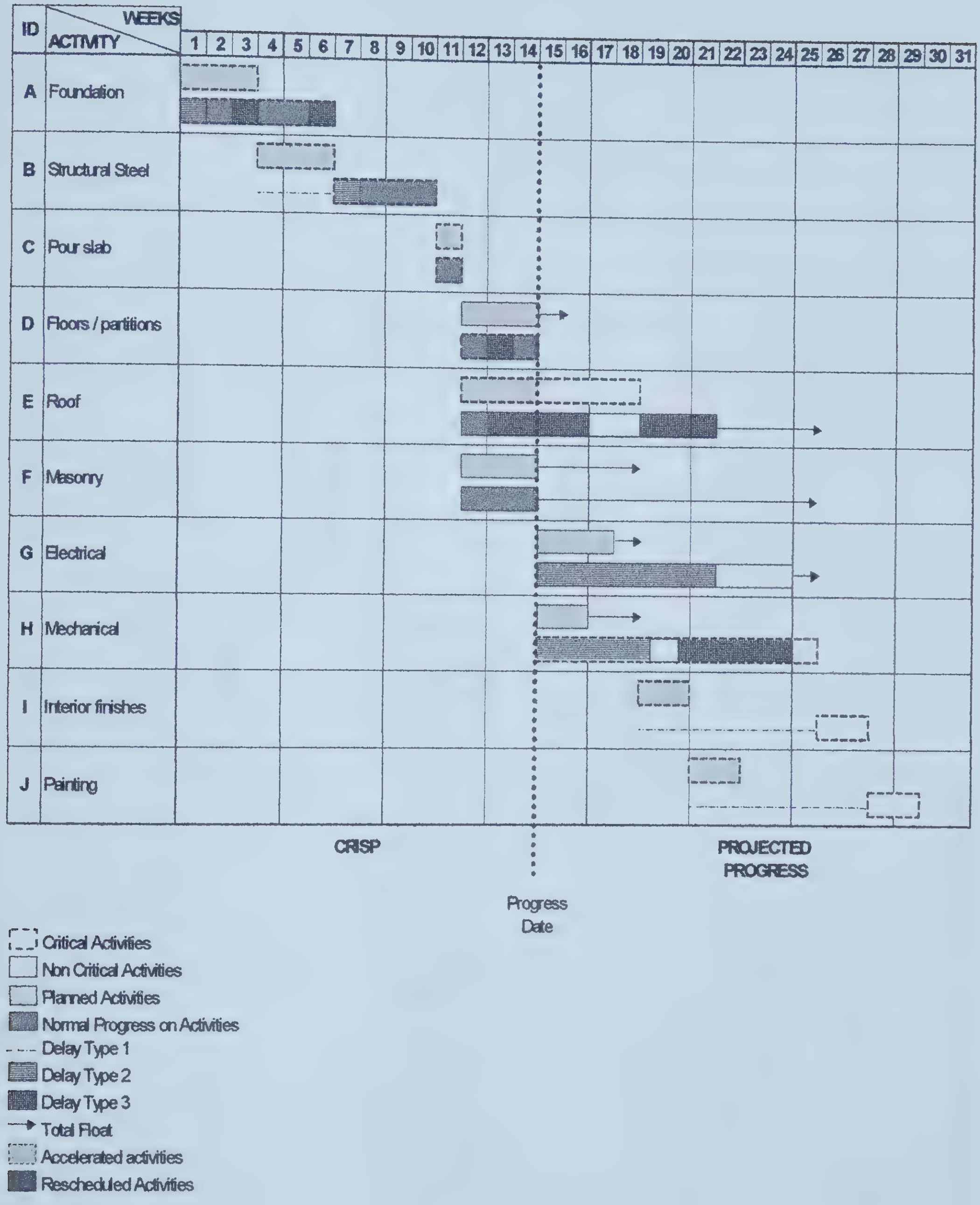


Figure A.15 Bar Chart Schedule - Third Snapshot

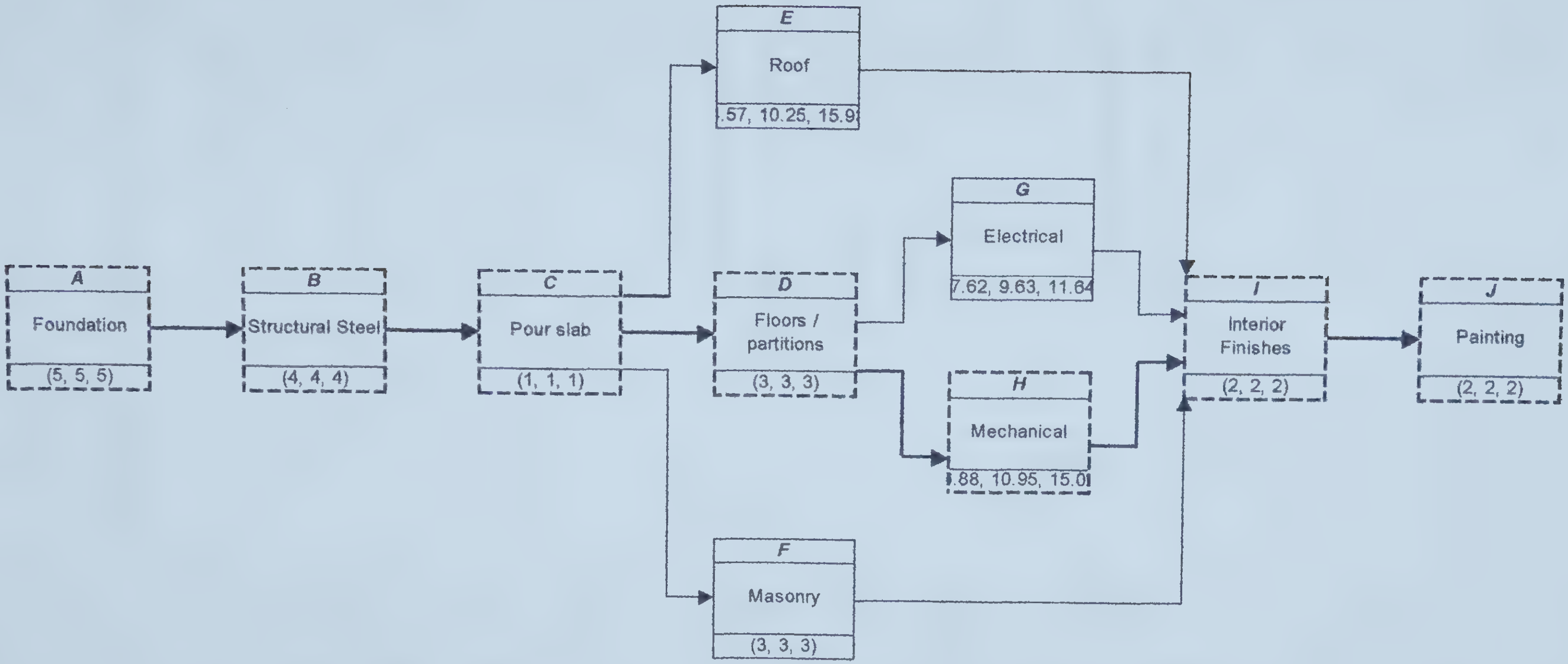


Figure A.16 Network Diagram Schedule - Third Snapshot

Activity:

E Roof

		Triangular Fuzzy Numbers
Original duration:	**3 weeks**	
Normal Progress:	1 week	(1 , 1 , 1)
		⊕
Delay Type 3 (1st) :	Mean 4.25, Variance 0.84	(1.44 , 4.25 , 7.06)
		⊕
Remaining duration:	2 weeks	(2 , 2 , 2)
		⊕
Delay Type 3 (2nd) :	Mean 3.00, Variance 0.87	(0.13 , 3.00 , 5.87)
Revised duration in weeks:		**(4.57 , 10.25 , 15.93)**

Activity:

G Electrical

		Triangular Fuzzy Numbers
Original duration:	**3 weeks**	
Delay Type 2 :	Mean 6.63, Variance 0.53 weeks	(4.62 , 6.63 , 8.64)
		⊕
Remaining duration:	3 weeks	(3 , 3 , 3)
Revised duration in weeks:		**(7.62 , 9.63 , 11.64)**

Activity:

H Mechanical

		Triangular Fuzzy Numbers
Original duration:	2 weeks	
Delay Type 2 (1st) :	4.46 0.55	(2.62 , 4.46 , 6.30)
		⊕
Remaining duration:	1 week	(1 , 1 , 1)
		⊕
Delay Type 3 (2nd) :	Mean 4.49, Variance 0.66	(2.26 , 4.49 , 6.72)
		⊕
Remaining duration:	1 week	(1 , 1 , 1)
Revised duration in weeks:		**(6.88 10.95 15.02)**

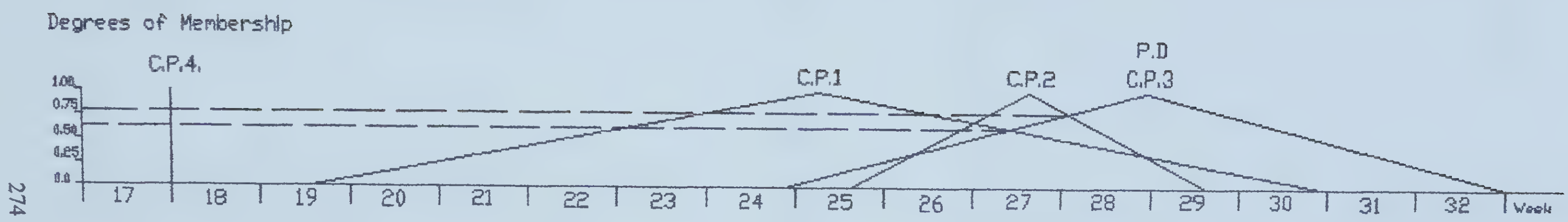
Figure A.17 Revised Activity Durations - Third Snapshot

ID	Activity	Fuzzy Duration	Fuzzy Early Start	Fuzzy Early Finish	Fuzzy Late Start	Fuzzy Late Finish	Total Float
A	Foundation	(6.00 , 6.00 , 6.00 , 6.00)	(0.00 , 0.00 , 0.00 , 0.00)	(6.00 , 6.00 , 6.00 , 6.00)	(0.00 , 0.00 , 0.00 , 0.00)	(6.00 , 6.00 , 6.00 , 6.00)	0.00
B	Structural Steel	(4.00 , 4.00 , 4.00 , 4.00)	(6.00 , 6.00 , 6.00 , 6.00)	(10.00 , 10.00 , 10.00 , 10.00)	(6.00 , 6.00 , 6.00 , 6.00)	(10.00 , 10.00 , 10.00 , 10.00)	0.00
C	Pour slab	(1.00 , 1.00 , 1.00 , 1.00)	(10.00 , 10.00 , 10.00 , 10.00)	(11.00 , 11.00 , 11.00 , 11.00)	(10.00 , 10.00 , 10.00 , 10.00)	(11.00 , 11.00 , 11.00 , 11.00)	0.00
D	Floors / partitions	(3.00 , 3.00 , 3.00 , 3.00)	(11.00 , 11.00 , 11.00 , 11.00)	(14.00 , 14.00 , 14.00 , 14.00)	(11.00 , 11.00 , 11.00 , 11.00)	(14.00 , 14.00 , 14.00 , 14.00)	0.00
E	Roof	(4.57 , 10.25 , 10.25 , 15.93)	(11.00 , 11.00 , 11.00 , 11.00)	(15.57 , 21.25 , 21.25 , 26.93)	(14.70 , 14.70 , 14.70 , 14.70)	(19.27 , 24.95 , 24.95 , 30.63)	3.70
F	Masonry	(3.00 , 3.00 , 3.00 , 3.00)	(11.00 , 11.00 , 11.00 , 11.00)	(14.00 , 14.00 , 14.00 , 14.00)	(21.95 , 21.95 , 21.95 , 26.02)	(24.95 , 24.95 , 24.95 , 29.02)	12.31
G	Electrical	(7.62 , 9.63 , 9.63 , 11.64)	(14.00 , 14.00 , 14.00 , 14.00)	(21.62 , 23.63 , 23.63 , 25.64)	(15.32 , 15.32 , 15.32 , 17.38)	(22.94 , 24.95 , 24.95 , 29.02)	2.01
H	Mechanical	(6.88 , 10.95 , 10.95 , 15.02)	(14.00 , 14.00 , 14.00 , 14.00)	(20.88 , 24.95 , 24.95 , 29.02)	(14.00 , 14.00 , 14.00 , 14.00)	(20.88 , 24.95 , 24.95 , 29.02)	0.00
I	Interior finishes	(2.00 , 2.00 , 2.00 , 2.00)	(20.88 , 24.95 , 24.95 , 29.02)	(22.88 , 26.95 , 26.95 , 31.02)	(20.88 , 24.95 , 24.95 , 29.02)	(22.88 , 26.95 , 26.95 , 31.02)	0.00
J	Painting	(2.00 , 2.00 , 2.00 , 2.00)	(22.88 , 26.95 , 26.95 , 31.02)	(24.88 , 28.95 , 28.95 , 33.02)	(22.88 , 26.95 , 26.95 , 31.02)	(24.88 , 28.95 , 28.95 , 33.02)	0.00

CRITICAL PATH DURATIONS:

1	A-B-C-E-I-J	(19.57 , 25.25 , 25.25 , 30.93)
2	A-B-C-D-G-I-J	(25.62 , 27.63 , 27.63 , 29.64)
3	A-B-C-D-H-I-J	(24.88 , 28.95 , 28.95 , 33.02)
4	A-B-C-F-I-J	(18.00 , 18.00 , 18.00 , 18.00)

Figure A.18 Fuzzy Schedule - Third Snapshot



Critical Paths:

C.P.1=A-B-C-E-I-J
C.P.2=A-B-C-D-G-I-J
C.P.3=A-B-C-D-H-I-J
C.P.4=A-B-C-F-I-J

Possibility Measure and Agreement Index:

PM1=0.68 AI1=0.74
PM2=0.82 AI2=0.51
PM3=1.00 AI3=1.00

Figure A.19 Project Duration and Critical Paths - Third Snapshot

ID	Activity	PM	ΣPM	AI	ΣAI
A	Foundation	1.00	2.50	1.00	2.25
B	Structural Steel	1.00	2.50	1.00	2.25
C	Pour slab	1.00	2.50	1.00	2.25
D	Floors / partitions	1.00	1.82	1.00	1.51
E	Roof	0.68	0.68	0.74	0.74
F	Masonry	0.00	0.00	0.00	0.00
G	Electrical	0.82	0.82	0.51	0.51
H	Mechanical	1.00	1.00	1.00	1.00
I	Interior finishes	1.00	2.50	1.00	2.25
J	Painting	1.00	2.50	1.00	2.25

Figure A.20 Criticality of Activities - Third Snapshot

ID	Activity	Original Duration Weeks	Actual Duration Weeks	Type of Delay	Effect of delays on the progress of the workss
A	Foundation	3	5	Type 1 Type 3 Type 3	Foundation is a critical activity and it suffered a sequencial combination of delays Type 2 and 3 that has the effect of delaying the project completion date. Activity Foundation remains being critical to the progress of the works after suffering the delays.
B	Structural Steel	3	4	Type 1 Type 2	Structural Steel is a critical activity and it suffered a a sequencial combination of delays Type 1 and 2 that has the effect of delaying the project completion date. Activity Structural Steel remains critical to
C	Pour slab	1	1	-	Work progess on activity Pour Slab proceded as planned with respect to the actual planned schedule.
D	Floors / partitions	2	3	Type 3	Floors / partitions was previously a non-critical activity and it suffered a delay Type 3 and has an actual duration of 3 weeks. The delay has the effect of delaying the project completion date. Activity Floors / partitions turned critical to the progress of the works after suffering the delay.
E	Roof	3	4.57 Lower Bound 10.25 Mean 15.93 Upper Bound	Type 3	Roof was previously a critical activity and it suffered a sequencial combination of two delays Type 3 that has no effect upon the completion of the works due to the float that it has with respect to activity Mechanical. Activity Roof turned non-critical to the progress of the works even though it suffered delay.
F	Masonry	3	3	-	Work progess on activity Masonry proceded as planned with respect to the actual planned schedule.
G	Electrical	3	7.62 Lower Bound 9.63 Mean 11.64 Upper Bound	Type 2	Electrical was previously a non-critical activity and it suffered a delay Type 2 that has no effect upon the completion of the works due to the float that it has with respect to activity Mechanical. Activity Electrical remains non-critical to the progress of the work after suffering the delay.
H	Mechanical	2	6.88 Lower Bound 10.95 Mean 15.02 Upper Bound	Type 2 Type 3	Mechanical was previously a non-critical activity and it suffered a sequencial combination of delays Type 2 and Type 3 that has the effect of delaying the project completion date. Activity Mechanical turned critical to the progress of the work after suffering the delay.
I	Interior finishes	2	2	Type 1	Interior finishes is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Interior finishes remains critical to the progress of the works after suffering the delay.
J	Painting	2	2	Type 1	Painting is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Painting remains critical to the progress of the works after suffering the delay.

Table A.4 Effects of Delays on the Schedule - Third Snapshot

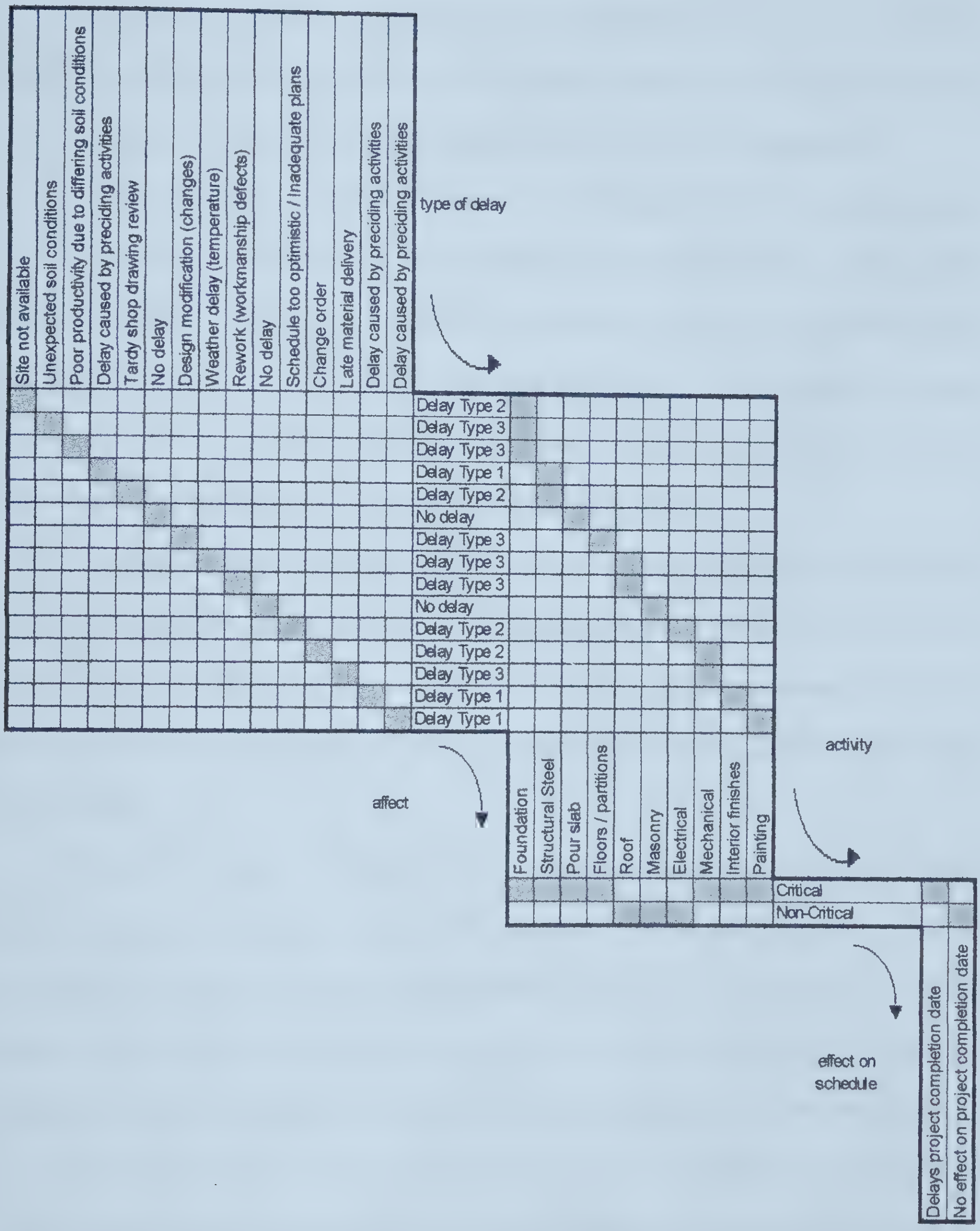


Figure A.21 Cause-Effect Matrix - Effects of Delays on the Schedule - Third Snapshot

A.2.4 Fourth Snapshot

The fourth snapshot was performed at the beginning of week 25, in order to update the schedule based on the fact that previous delays were completed. For this reason, all activity durations are known with certainty and thus are crisp values.

As can be observed on the bar chart corresponding to the fourth snapshot (Figure 4.22), activities I, "Interior Finishes" and J, "Painting" were rescheduled by modifying their logic relationships. Also, activity J, "Painting" was accelerated so that only half the time of its original duration is required. These measures were taken when the project was close to finishing in order to minimize the impact of delays, although some of these measures could have been applied at any time during the project execution.

The network diagram in Figure 4.23 incorporates the actual logic relationships and durations. Computations for actual early and late finish times are included in Figure 4.24. Table 5 and Figure A.25 indicate the effects of rescheduling and acceleration on the schedule. The as-built database records corresponding to the first snapshot are included in Appendix D.

Activities I, "Interior Finishes", and J, "Painting" remained critical after being rescheduled and accelerated in the fourth snapshot. The critical path changed from activities A-B-C-D-H-I-J to two new critical paths: A-B-C-D-G-I and A-B-C-D-H-J. For this reason, activities Floors and Partitions and Electrical that were non-critical in the third snapshot schedule, became critical. The project completion time on the third snapshot was (24.88, 28.95, 33.02) weeks, and after the measures taken, the actual project completion time is 26 weeks. Rescheduling and accelerating the activities reduced the project duration by 3 weeks, from 29 weeks to 26 weeks.

[illegible]

[illegible]

[illegible]

[illegible]

Figure A.26 presents the as-planned and as-built schedule showing that the net delay that affected the project completion time was 10 weeks.

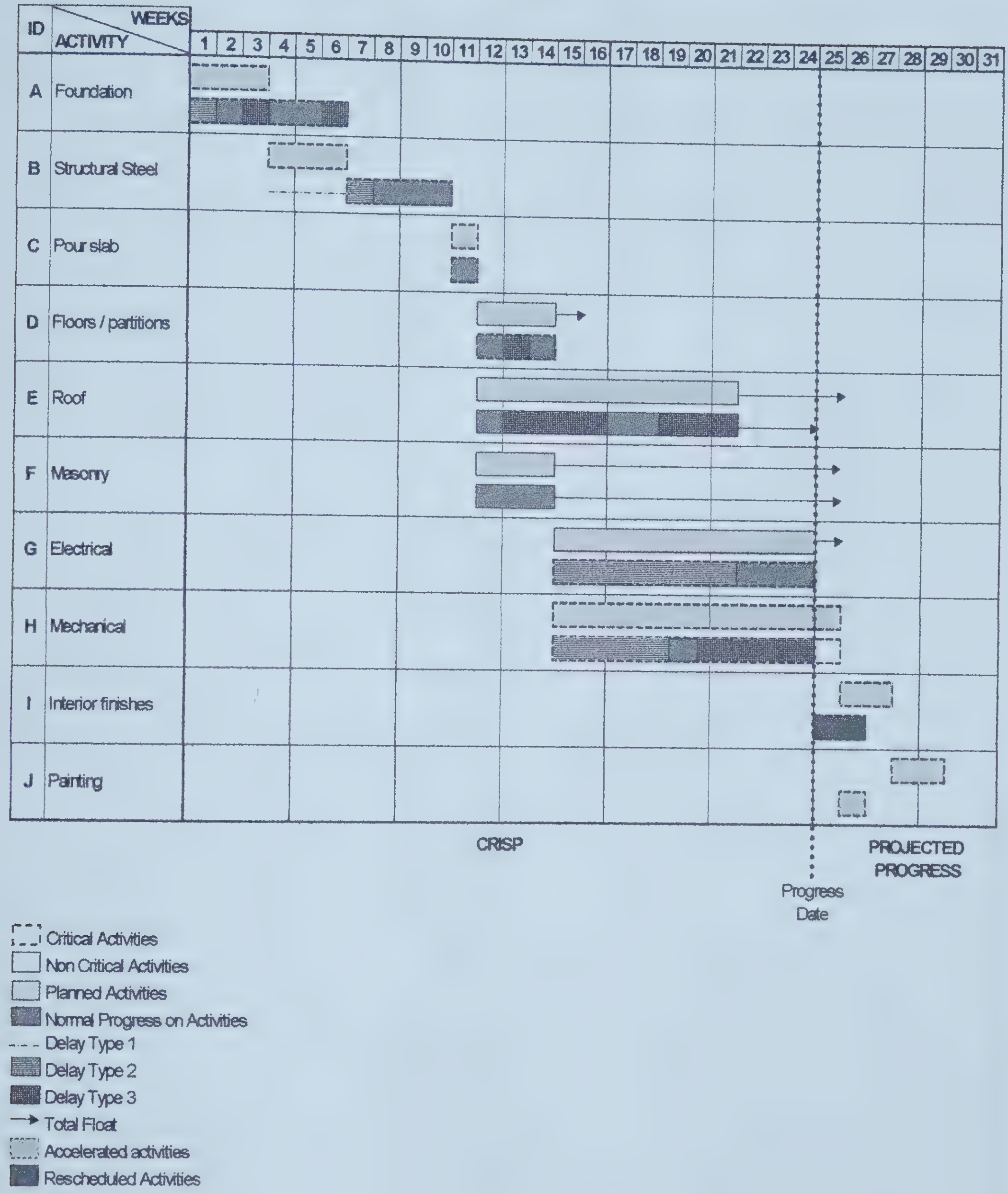


Figure A.22 Bar Chart Schedule - Fourth Snapshot

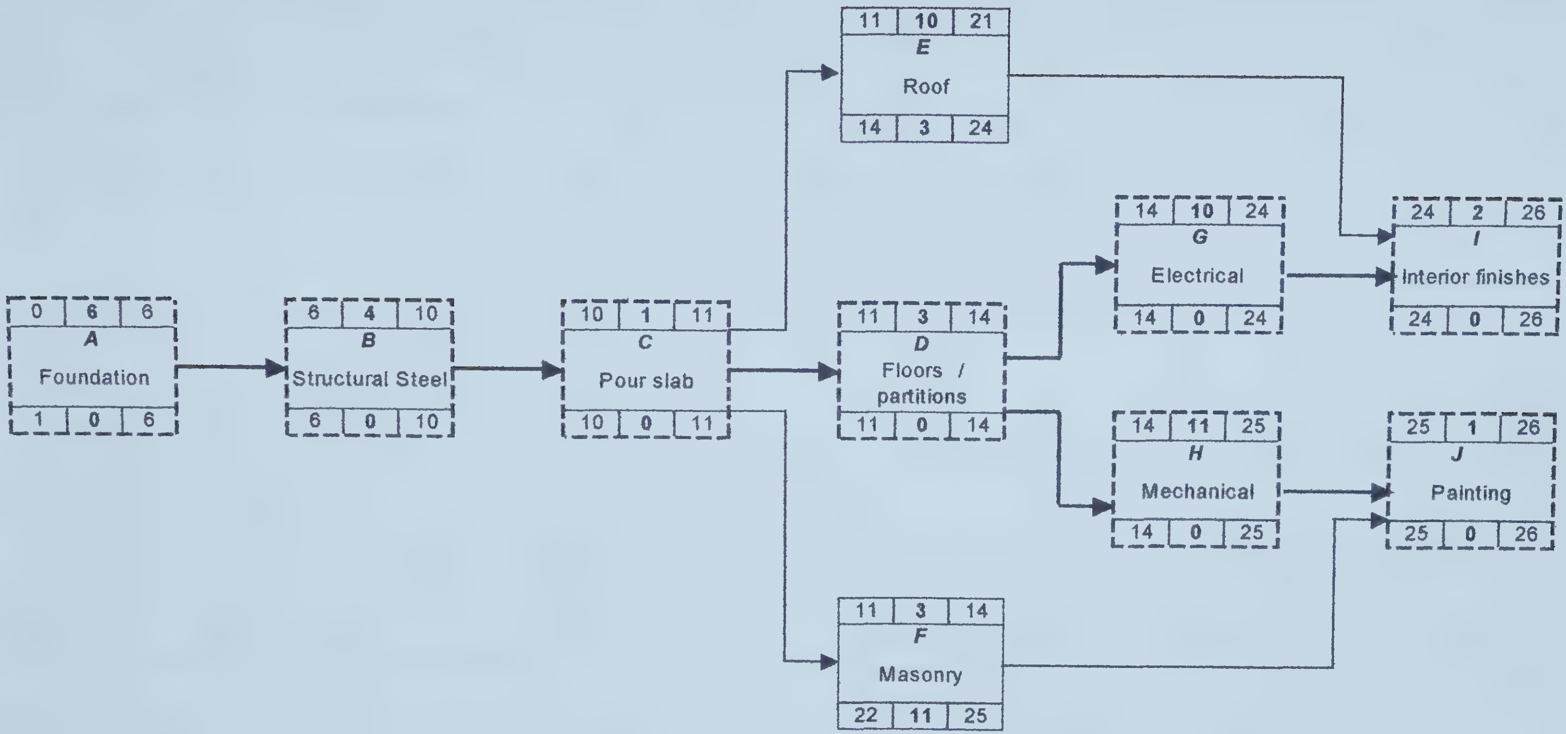


Figure A.23 Network Diagram Schedule - Fourth Snapshot

ID	Activity	Fuzzy Duration	Fuzzy Early Start	Fuzzy Early Finish	Fuzzy Late Start	Fuzzy Late Finish	Total Float
A	Foundation	(6 , 6 , 6 , 6)	(0 , 0 , 0 , 0)	(6 , 6 , 6 , 6)	(0 , 0 , 0 , 0)	(6 , 6 , 6 , 6)	0
B	Structural Steel	(4 , 4 , 4 , 4)	(6 , 6 , 6 , 6)	(10 , 10 , 10 , 10)	(6 , 6 , 6 , 6)	(10 , 10 , 10 , 10)	0
C	Pour slab	(1 , 1 , 1 , 1)	(10 , 10 , 10 , 10)	(11 , 11 , 11 , 11)	(10 , 10 , 10 , 10)	(11 , 11 , 11 , 11)	0
D	Floors / partitions	(3 , 3 , 3 , 3)	(11 , 11 , 11 , 11)	(14 , 14 , 14 , 14)	(11 , 11 , 11 , 11)	(14 , 14 , 14 , 14)	0
E	Roof	(10 , 10 , 10 , 10)	(11 , 11 , 11 , 11)	(21 , 21 , 21 , 21)	(14 , 14 , 14 , 14)	(24 , 24 , 24 , 24)	3
F	Masonry	(3 , 3 , 3 , 3)	(11 , 11 , 11 , 11)	(14 , 14 , 14 , 14)	(22 , 22 , 22 , 22)	(25 , 25 , 25 , 25)	11
G	Electrical	(10 , 10 , 10 , 10)	(14 , 14 , 14 , 14)	(24 , 24 , 24 , 24)	(14 , 14 , 14 , 14)	(24 , 24 , 24 , 24)	0
H	Mechanical	(11 , 11 , 11 , 11)	(14 , 14 , 14 , 14)	(25 , 25 , 25 , 25)	(14 , 14 , 14 , 14)	(25 , 25 , 25 , 25)	0
I	Interior finishes	(2 , 2 , 2 , 2)	(24 , 24 , 24 , 24)	(26 , 26 , 26 , 26)	(24 , 24 , 24 , 24)	(26 , 26 , 26 , 26)	0
J	Painting	(1 , 1 , 1 , 1)	(25 , 25 , 25 , 25)	(26 , 26 , 26 , 26)	(25 , 25 , 25 , 25)	(26 , 26 , 26 , 26)	0

Figure A.24 Fuzzy Schedule - Fourth Snapshot

ID	Activity	Original Duration Weeks	Actual Duration Weeks	Type of Delay	Effect of delays on the progress of the works
A	Foundation	3	5	Type 1 Type 3 Type 3	Foundation is a critical activity and it suffered a sequencial combination of delays Type 2 and 3 that has the effect of delaying the project completion date. Activity Foundation remains being critical to the progress of the works after suffering the delays.
B	Structural Steel	3	4	Type 1 Type 2	Structural Steel is a critical activity and it suffered a a sequencial combination of delays Type 1 and 2 that has the effect of delaying the project completion date. Activity Structural Steel remains critical to the progress of
C	Pour slab	1	1	-	Work progess on activity Pour Slab proceded as planned with respect to the actual planned schedule.
D	Floors / partitions	2	3	Type 3	Floors / partitions was previously a non-critical activity and it suffered a delay Type 3 and has an actual duration of 3 weeks. The delay has the effect of delaying the project completion date. Activity Floors / partitions turned critical to the progress of the works after suffering the delay.
E	Roof	3	10	Type 3	Roof was previously a non-critical activity and it suffered a sequencial combination of two delays Type 3 that has no effect upon the completion of the works due to the float that it has with respect to activity Mechanical. Activity Roof remains being non-critical to the progress of the works after suffering the delays.
F	Masonry	3	3	-	Work progess on activity Masonry proceded as planned with respect to the actual planned schedule.
G	Electrical	3	10	Type 2	Electrical was previously a non-critical activity and it suffered a delay Type 2 that has the effect of delaying the project completion date due to the new precedence relation imposed by rescheduling activity Interior finishes. Activity Electrical is now critical to the progress of the work after suffering the delay.
H	Mechanical	2	11	Type 2 Type 3	Mechanical was previously a critical activity and it suffered a sequencial combination of delays Type 2 and Type 3 that has the effect of delaying the project completion date due to the new precedence relation imposed by rescheduling activity Painting. Activity Mechanical turned critical to the progress of the work after suffering the delay.
I	Interior finishes	2	2	Type 1	Interior finishes is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Interior finishes was rescheduled and remains critical to the progress of the works after suffering the delay.
J	Painting	2	1	Type 1	Painting is a critical activity and it suffered a delay Type 1 that has the effect of delaying the project completion date. Activity Painting was accelerated and rescheduled, and remains critical to the progress of the works after suffering the delay.

Table A.5 Effects of Delays on the Schedule - Fourth Snapshot

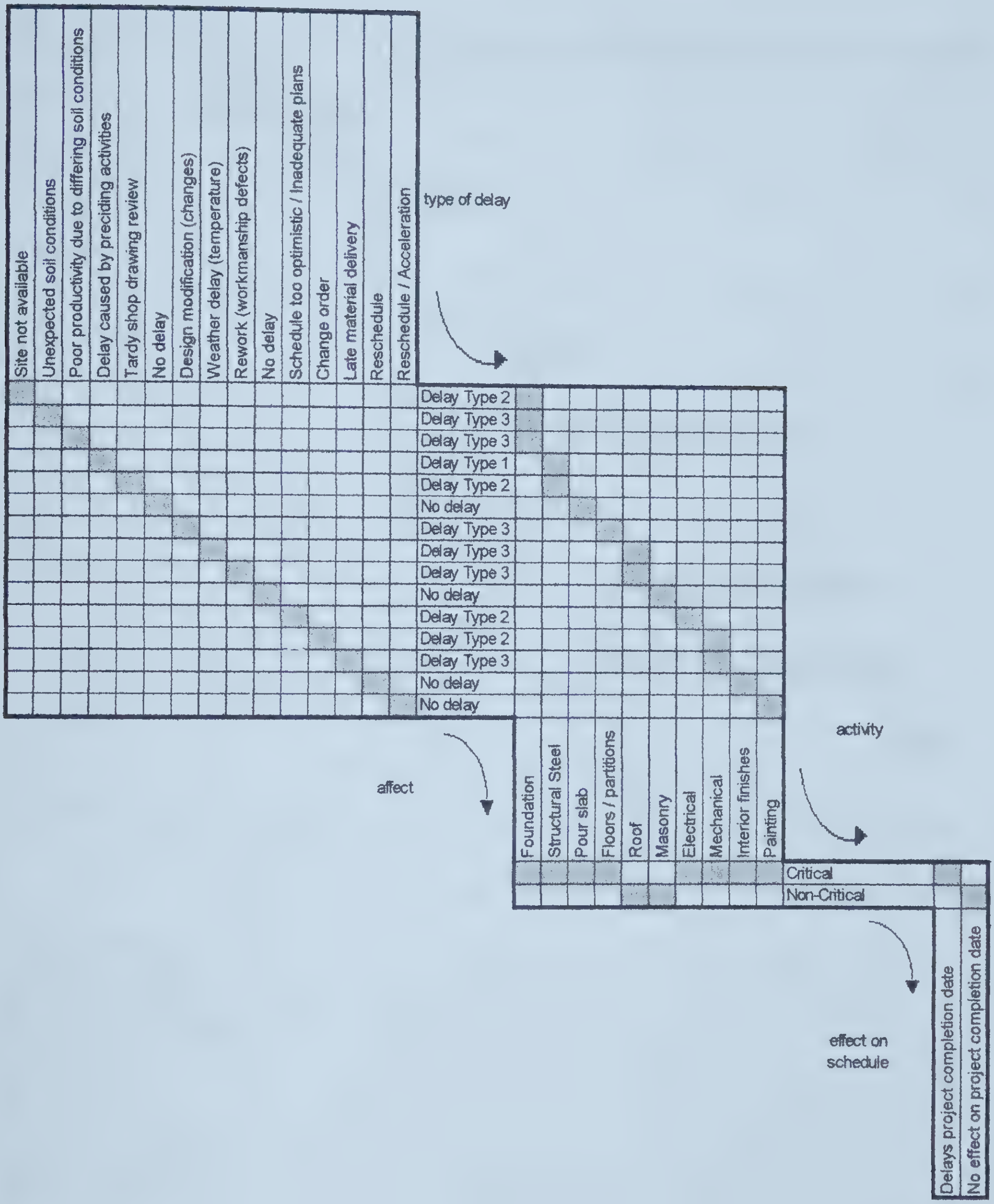


Figure A.25 Cause-Effect Matrix - Effects of Delays on the Schedule - Fourth Snapshot

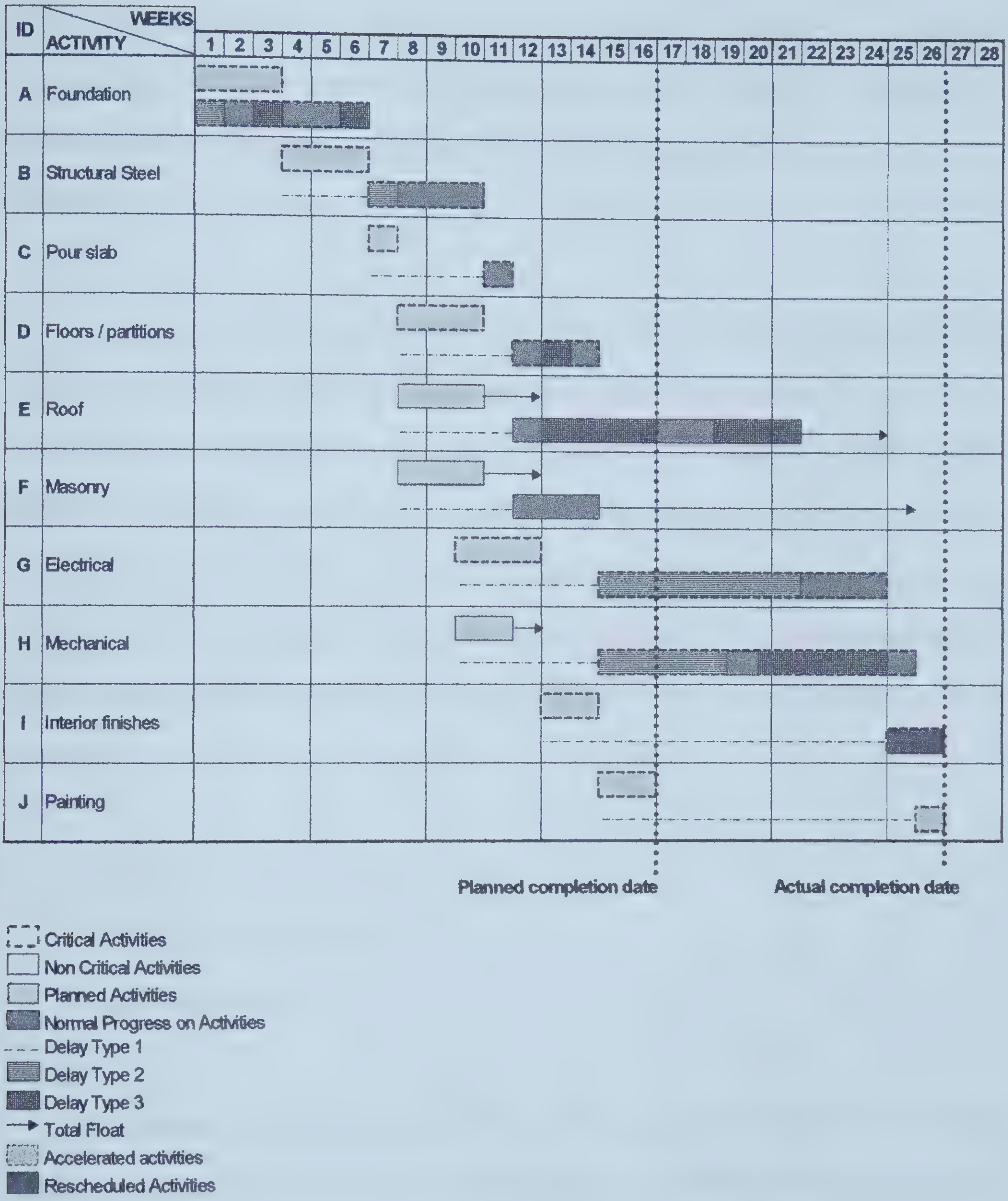


Figure A.26 As-Planned vs. As-Built Schedule

A.3 Estimation of Delay Impacts

This section illustrates the methodology presented in Section 3.5 to estimate delay impacts. Activity Electrical on the third snapshot is used to exemplify the calculations of the method. The procedure is explained using the steps presented on Section 3.5.2.

- Step 1: The user selects three delay-sensitive attributes that determine the sensitivity of activity G, "Electrical" to the delay it will suffer due to unplanned work during winter. The user selects these three attributes based on the description of the situation that led to the delay, as well as the causes of the delay (Refer to Table A.1 and Figure A.3). The user utilizes this information, to identify the delay-sensitive attributes that related to the delay and its corresponding linguistic states. The three delay-sensitive attributes of activity that determine the specific effect of the delay on the activity are as follows:

- Sensitivity to duration of the activity
- Sensitivity to precipitation
- Sensitivity to wind

The sensitivity to the Duration of the activity was considered due to the time exposure. The linguistic states to be considered for the sensitivity to duration will be as follows: Long duration, Medium duration and Short duration. The sensitivity to precipitation is due to the fact that the building needed to be watertight, before the electrical conduits could be commenced. The linguistic states to be considered for the

sensitivity to precipitation will be as follows: High sensitivity to precipitation, Average sensitivity to precipitation, and Low sensitivity to precipitation.

The sensitivity to Wind is due to the fact that the building needed to be protected from wind before the electrical conduits could be commenced. The linguistic states to be considered for the sensitivity to wind will be as follows: High sensitivity to wind, Average sensitivity to wind, and Low sensitivity to wind.

• Step 2: The user estimates the relationship between the state of each attribute and its frequency of occurrence in linguistic terms. For each attribute state, the user determines the frequency of occurrence with which the delay under consideration will likely affect the activity.

• Step 3: The user estimates the relationship between the frequency of occurrence of the state of each attribute and its adverse consequences in linguistic terms. For each frequency of occurrence of the state of each attribute, the user determines the adverse consequences that the occurrence of the delay will produce.

In theory, the number of all possible relationships between the frequency of occurrence of a specific state and its adverse consequences is large. However, the number of possible relationships is reduced based on practical consideration and the intuition of the user. The appropriate choice of relation also results from analyzing the situation and causes that lead to the delay (Refer to Table A.1 and Figure A.3), as well as the characteristics of the activity. This analysis reveals the most likely relation between the frequency of occurrence of a specific state and its adverse consequences. The user produced the following assessments with respect to the three delay-sensitive attributes for activity G, "Electrical", for the most likely situation in which the activity is affected by a

delay due to unplanned work during winter that has a likely Large frequency of occurrence:

- Activity G, "Electrical" has a Large duration and it may be affected by a delay due to unplanned work during winter that has a likely Large frequency of occurrence. The delay will have Very Large consequences if it should occur.
- Activity G, "Electrical" has a High sensitivity to precipitation and it may be affected by a delay due to unplanned work during winter that has a likely Large frequency of occurrence. The delay will have Very Large consequences if it should occur.
- Activity G, "Electrical" has High sensitivity to wind and it may be affected by a delay due to unplanned work during winter that has a likely Large frequency of occurrence. The delay will have Very Large consequences if it should occur.

Since the frequency of occurrence and adverse consequences of the delay are beyond the control of the user, the outcome of the delay can not be known with absolute certainty. The nature of this situation is fuzzy and the outcome of the delay could deviate from the most likely situation. Different logical outcomes are also considered to represent the extent of the potential damage if the delay should occur. The following are the user's subjective assessments to account for other possible outcomes with respect to the three delay-sensitive attributes activity G, "Electrical".

[illegible]

[illegible]

[illegible]

[illegible]

If the duration of the activity is Long, then the likely frequency of occurrence of a delay due to unplanned work during winter is Large, and the adverse consequences that this delay generates are Very Large. If the duration of the activity is Medium, then the likely frequency of occurrence of a delay due to unplanned work during winter is Large, and the adverse consequences that this delay generates are Large. If the duration of the activity is Short, then the likely frequency of occurrence of a delay due to unplanned work during winter is Small, and the adverse consequences that this delay generates are Large.

If the activity is taking place in an area where the exposure to precipitation is High, then the likely frequency of occurrence of a delay due to unplanned work during winter is Large, and the adverse consequences that this delay generates are Very Large. If the activity is taking place in an area where the exposure to precipitation is Average, then the likely frequency of occurrence of a delay due to unplanned work during winter is Small, and the adverse consequences that this delay generates are Medium. If the activity is taking place in an area where the exposure to precipitation is Low, then the likely frequency of occurrence of a delay due to unplanned work during winter is Large, and the adverse consequences that this delay generates are Large.

If the activity is taking place in an area where the exposure to wind is High, then the likely frequency of occurrence of a delay due to unplanned work during winter is Large, and the adverse consequences that this delay generates are Very Large. If the activity is taking place in an area where the exposure to wind is Average, then the likely frequency of occurrence of a delay due to unplanned work during winter is Small, and the adverse consequences that this delay generates are Medium. If the activity is taking place in an area where the exposure to wind is Low, then the likely frequency of

[illegible]

[illegible]

[illegible]

occurrence of a delay due to unplanned work during winter is Medium, and the adverse consequences that this delay generates are Medium.

Table A.6 contains all subjective assessments produced by the user in order to portray the complete picture of the occurrence of the delay due to unplanned work during winter that affects activity G, "Electrical".

Table A.6 Delay sensitive attributes for activity G, "Electrical".

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Large Large Small	Very Large Large Large
Precipitation	High Average Low	Large Small Large	Very Large Medium Large
Wind	High Average Low	Large Small Medium	Very Large Medium Medium

- Step 4: The user translates the linguistic terms into fuzzy sets by assigning membership values to each linguistic term describing the frequency of occurrence and adverse consequences. Equations (3-1) to (3-7) in Section 3.5.2 are used in this example to translate linguistic variables into fuzzy sets. Tables A.7 to A.15 show the membership values for the relations between Frequency of Occurrence and Adverse consequences for the delay attributes: Duration, Precipitation and Wind.

[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

Table A.7 Membership Values for Occurrence and Consequences related to delay attribute Long Duration

Duration

State	Long
Frequency of occurrence:	Large
Adverse Consequences:	Very Large

Elements	Frequency of Occurrence	Adverse Consequences
0	0.00	0.00
0.1	0.00	0.00
0.2	0.00	0.00
0.3	0.00	0.00
0.4	0.00	0.00
0.5	0.00	0.00
0.6	0.00	0.00
0.7	0.00	0.00
0.8	0.50	0.25
0.9	0.90	0.81
1	1.00	1.00
Linguistic Variable	**Large**	**Very Large**

Table A.8 Membership Values for Occurrence and Consequences related to delay attribute Medium Duration

Duration

State	Medium
Frequency of occurrence:	Large
Adverse Consequences:	Large

Elements	Frequency of Occurrence	Adverse Consequences
0	0.00	0.00
0.1	0.00	0.00
0.2	0.00	0.00
0.3	0.00	0.00
0.4	0.00	0.00
0.5	0.00	0.00
0.6	0.00	0.00
0.7	0.00	0.00
0.8	0.50	0.50
0.9	0.90	0.90
1	1.00	1.00
Linguistic Variable	**Large**	**Large**

Table A.9 Membership Values for Occurrence and Consequences related to delay attribute Short Duration

Duration

State	Short
Frequency of occurrence:	Small
Adverse Consequences:	Large

Elements	Frequency of Occurrence	Adverse Consequences
0	1.00	0.00
0.1	0.90	0.00
0.2	0.50	0.00
0.3	0.00	0.00
0.4	0.00	0.00
0.5	0.00	0.00
0.6	0.00	0.00
0.7	0.00	0.00
0.8	0.00	0.50
0.9	0.00	0.90
1	0.00	1.00
Linguistic Variable	**Small**	**Large**

Table A.10 Membership Values for Occurrence and Consequences related to delay attribute High Precipitation

Precipitation

State:	High
Frequency of occurrence:	Large
Adverse Consequences:	Very Large

Elements	Frequency of Occurrence	Adverse Consequences
0	0.00	0.00
0.1	0.00	0.00
0.2	0.00	0.00
0.3	0.00	0.00
0.4	0.00	0.00
0.5	0.00	0.00
0.6	0.00	0.00
0.7	0.00	0.00
0.8	0.50	0.25
0.9	0.90	0.81
1	1.00	1.00
Linguistic Variable	**Large**	**Very Large**

Table A.11 Membership Values for Occurrence and Consequences related to delay attribute Average Precipitation

Precipitation

State:	Average
Frequency of occurrence:	Small
Adverse Consequences:	Medium

Elements	Frequency of Occurrence	Adverse Consequences
0	1.00	0.00
0.1	0.90	0.00
0.2	0.50	0.00
0.3	0.00	0.20
0.4	0.00	0.80
0.5	0.00	1.00
0.6	0.00	0.80
0.7	0.00	0.20
0.8	0.00	0.00
0.9	0.00	0.00
1	0.00	0.00
Linguistic Variable	**Small**	**Medium**

Table A.12 Membership Values for Occurrence and Consequences related to delay attribute Low Precipitation

Precipitation

State:	Low
Frequency of occurrence:	Large
Adverse Consequences:	Large

Elements	Frequency of Occurrence	Adverse Consequences
0	0.00	0.00
0.1	0.00	0.00
0.2	0.00	0.00
0.3	0.00	0.00
0.4	0.00	0.00
0.5	0.00	0.00
0.6	0.00	0.00
0.7	0.00	0.00
0.8	0.50	0.50
0.9	0.90	0.90
1	1.00	1.00
Linguistic Variable	**Large**	**Large**

[illegible]

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

[illegible]

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

Table A.13 Membership Values for Occurrence and Consequences related to delay attribute High Wind

Wind
State High
Frequency of occurrence: Large
Adverse Consequences: Very Large

Elements	Frequency of Occurrence	Adverse Consequences
0	0.00	0.00
0.1	0.00	0.00
0.2	0.00	0.00
0.3	0.00	0.00
0.4	0.00	0.00
0.5	0.00	0.00
0.6	0.00	0.00
0.7	0.00	0.00
0.8	0.50	0.25
0.9	0.90	0.81
1	1.00	1.00
Linguistic Variable	**Large**	**Very Large**

Table A.14 Membership Values for Occurrence and Consequences related to delay attribute Average Wind

Wind
State Average
Frequency of occurrence: Small
Adverse Consequences: Medium

Elements	Frequency of Occurrence	Adverse Consequences
0	1.00	0.00
0.1	0.90	0.00
0.2	0.50	0.00
0.3	0.00	0.20
0.4	0.00	0.80
0.5	0.00	1.00
0.6	0.00	0.80
0.7	0.00	0.20
0.8	0.00	0.00
0.9	0.00	0.00
1	0.00	0.00
Linguistic Variable	**Small**	**Medium**

Table A.15 Membership Values for Occurrence and Consequences related to delay attribute Low Wind

Wind	
State	Low
Frequency of occurrence:	Medium
Adverse Consequences:	Medium

Elements	Frequency of Occurrence	Adverse Consequences
0	0.00	0.00
0.1	0.00	0.00
0.2	0.00	0.00
0.3	0.20	0.20
0.4	0.80	0.80
0.5	1.00	1.00
0.6	0.80	0.80
0.7	0.20	0.20
0.8	0.00	0.00
0.9	0.00	0.00
1	0.00	0.00
Linguistic Variable	**Medium**	**Medium**

- Step 5: The fuzzy logic model combines the frequency of occurrence and adverse consequences for each attribute state. The fuzzy logic model calculates fuzzy relation matrices, or Cartesian product $F \times C$, between the fuzzy subsets F, representing the frequency of occurrence, and the fuzzy subsets C, representing the adverse consequences. Figures A.27 to A.35 depict the fuzzy relationships obtained:

Adverse Consequences

Frequency of Occurrence	**0.8**	**0.9**	**1.0**
0.8	0.25	0.25	0.25
0.9	0.25	0.81	0.81
1.0	0.25	0.81	1.00

Figure A.27 Relationship R_1 between Frequency of Occurrence (F_1) and Adverse Consequences (C_1) for example project: $R_1 = F_1 \times C_1$

Adverse Consequences

Frequency of Occurrence	0.8	0.9	1.0
0.8	0.50	0.50	0.50
0.9	0.50	0.90	0.90
1.0	0.50	0.90	1.00

Figure A.28 Relationship R_2 between Frequency of Occurrence (F_2) and Adverse Consequences (C_2) for example project: $R_2 = F_2 \times C_2$

Adverse Consequences

Frequency of Occurrence	0.8	0.9	1.0
0.0	0.50	1.00	1.00
0.1	0.50	0.90	0.90
0.2	0.50	0.50	0.50

Figure A.29 Relationship R_3 between Frequency of Occurrence (F_3) and Adverse Consequences (C_3) for example project: $R_3 = F_3 \times C_3$

Adverse Consequences

Frequency of Occurrence	0.8	0.9	1.0
0.8	0.25	0.50	0.50
0.9	0.25	0.81	0.90
1.0	0.25	0.81	1.00

Figure A.30 Relationship R_4 between Frequency of Occurrence (F_4) and Adverse Consequences (C_4) for example project: $R_4 = F_4 \times C_4$

Adverse Consequences

Frequency of Occurrence	0.3	0.4	0.5	0.6	0.7
0.0	0.20	0.80	1.00	0.80	0.20
0.1	0.20	0.80	0.90	0.80	0.20
0.2	0.20	0.50	0.50	0.50	0.20

Figure A.31 Relationship R_5 between Frequency of Occurrence (F_5) and Adverse Consequences (C_5) for example project: $R_5 = F_5 \times C_5$

Adverse Consequences

Frequency of Occurrence	0.8	0.9	1.0
0.8	0.50	0.50	0.50
0.9	0.50	0.90	0.90
1.0	0.50	0.90	1.00

Figure A.32 Relationship R_6 between Frequency of Occurrence (F_6) and Adverse Consequences (C_6) for example project: $R_6 = F_6 \times C_6$

Adverse Consequences

Frequency of Occurrence	0.8	0.9	1.0
0.8	0.25	0.50	0.50
0.9	0.25	0.81	0.90
1.0	0.25	0.81	1.00

Figure A.33 Relationship R_7 between Frequency of Occurrence (F_7) and Adverse Consequences (C_7) for example project: $R_7 = F_7 \times C_7$

Adverse Consequences

Frequency of Occurrence	0.3	0.4	0.5	0.6	0.7
0.0	0.20	0.80	1.00	0.80	0.20
0.1	0.20	0.80	0.90	0.80	0.20
0.2	0.20	0.50	0.50	0.50	0.20

Figure A.34 Relationship R_8 between Frequency of Occurrence (F_8) and Adverse Consequences (C_8) for example project: $R_8 = F_8 \times C_8$

Adverse Consequences

Frequency of Occurrence	0.3	0.4	0.5	0.6	0.7
0.3	0.20	0.20	0.20	0.20	0.20
0.4	0.20	0.80	0.80	0.80	0.20
0.5	0.20	0.80	1.00	0.80	0.20
0.6	0.20	0.80	0.80	0.80	0.20
0.7	0.20	0.20	0.20	0.20	0.20

Figure A.35 Relationship R_9 between Frequency of Occurrence (F_9) and Adverse Consequences (C_9) for example project: $R_9 = F_9 \times C_9$

- Step 6: After the fuzzy relation matrices have been developed, the fuzzy logic model performs the union matrix of all the relation matrices obtained. Figure A.36 shows the union matrix obtained.

Adverse Consequences

Frequency of Occurrence	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
0	0.00	0.00	0.00	0.20	1.00	1.00	0.80	0.20	0.50	1.00	1.00
0.1	0.00	0.00	0.00	0.20	0.90	0.90	0.80	0.20	0.50	0.90	0.90
0.2	0.00	0.00	0.00	0.20	0.50	0.50	0.50	0.20	0.50	0.50	0.50
0.3	0.00	0.00	0.00	0.20	0.20	0.20	0.20	0.20	0.00	0.00	0.00
0.4	0.00	0.00	0.00	0.20	0.80	0.80	0.80	0.20	0.00	0.00	0.00
0.5	0.00	0.00	0.00	0.20	0.80	1.00	0.80	0.20	0.00	0.00	0.00
0.6	0.00	0.00	0.00	0.20	0.80	0.80	0.80	0.20	0.00	0.00	0.00
0.7	0.00	0.00	0.00	0.20	0.20	0.20	0.20	0.20	0.00	0.00	0.00
0.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50
0.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.90	0.90
1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.90	1.00

Figure A.36 Union Matrix for Example Project: $T = (F_1 \times C_1) \cup (F_2 \times C_2) \cup (F_3 \times C_3) \cup (F_4 \times C_4) \cup (F_5 \times C_5) \cup (F_6 \times C_6) \cup (F_7 \times C_7) \cup (F_8 \times C_8) \cup (F_9 \times C_9)$

- Step 7: The user assesses the relationship between the adverse consequences and the delay duration for the activity in question. The user establishes his or her linguistic perception with respect to the delay duration, based on the magnitude or gravity of the adverse consequences on the delay duration. For example: If the consequences are large, then the delay duration is very large; if the consequences are medium, then the delay duration is large; if the consequences are small, then the delay duration is very small.

- Step 8: The user translates the linguistic terms into fuzzy sets by assigning membership values to each linguistic term describing the adverse consequences and delay duration. The membership functions of these relations are shown in Figure A.37. Based on his or her subjective judgment, the user establishes membership functions in order to express his or her belief of delay duration. This subjective judgment depends on the causes of the delay and on the activity and project characteristics. In this case the

user considered a delay duration of 7 days as definitely being very large, and a delay duration of 3 days as definitely being very small.

Delay duration in weeks:

Elements	(1) Very Large	(2) Large	(3) Very Small
3	0.00	0.00	1.00
4	0.00	0.00	0.64
5	0.04	0.20	0.04
6	0.49	0.70	0.00
7	1.00	1.00	0.00

Adverse Consequences:

Elements	(1) Large	(2) Medium	(3) Small
0	0.00	0.00	1.00
0.1	0.00	0.00	0.90
0.2	0.00	0.00	0.50
0.3	0.00	0.20	0.00
0.4	0.00	0.80	0.00
0.5	0.00	1.00	0.00
0.6	0.00	0.80	0.00
0.7	0.00	0.20	0.00
0.8	0.50	0.00	0.00
0.9	0.90	0.00	0.00
1	1.00	0.00	0.00

Figure A.37 Membership Functions for Delay Duration for Example Project

- Step 9: The fuzzy logic model combines the adverse consequences and delay duration. This is done by calculating fuzzy relation matrices, or cartesian products *C* x *D*, between the fuzzy subsets *C*, representing the adverse consequences, and the fuzzy subsets *D*, representing the delay duration. Figures A.38, A.39 and A.40 depict the fuzzy relationships obtained:

[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

Delay Duration

Adverse Consequences	5	6	7
0.8	0.09	0.36	0.50
0.9	0.09	0.36	0.90
1.0	0.09	0.36	1.00

Figure A.38 Relationship Q_1 between Adverse Consequences (C_1) and Delay Duration (D_1) for Example Project: $Q_1 = C_1 \times D_1$

Delay Duration

Adverse Consequences	3	4	5	6	7
0.3	0.10	0.20	0.20	0.20	0.20
0.4	0.10	0.30	0.60	0.80	0.80
0.5	0.10	0.30	0.60	0.80	1.00
0.6	0.10	0.30	0.60	0.80	0.80
0.7	0.10	0.20	0.20	0.20	0.20

Figure A.39 Relationship Q_2 between Adverse Consequences (C_2) and Delay Duration (D_2) for Example Project: $Q_2 = C_2 \times D_2$

Delay Duration

Adverse Consequences	3	4	5
0.0	1.00	0.64	0.04
0.1	0.90	0.64	0.04
0.2	0.50	0.50	0.04

Figure A.40 Relationship Q_3 between Adverse Consequences (C_3) and Delay Duration (D_3) for Example Project: $Q_3 = C_3 \times D_3$

- Step 10: After the above fuzzy relation matrices have been developed, the fuzzy logic model performs the union matrix of all the relation matrices obtained. Figure A.41 shows the union matrix obtained.

Delay Duration

Adverse Consequences	3	4	5	6	7
0	1.00	0.25	0.04	0.00	0.00
0.1	0.90	0.25	0.04	0.00	0.00
0.2	0.50	0.25	0.04	0.00	0.00
0.3	0.00	0.00	0.20	0.20	0.20
0.4	0.00	0.00	0.20	0.80	0.80
0.5	0.00	0.00	0.20	0.80	1.00
0.6	0.00	0.00	0.20	0.80	0.80
0.7	0.00	0.00	0.20	0.20	0.20
0.8	0.00	0.00	0.04	0.50	0.50
0.9	0.00	0.00	0.04	0.64	0.90
1.0	0.00	0.00	0.04	0.64	1.00

Figure A.41 Total Effect Matrix for Example Project: $V= (C_1 \times D_1)\ U\ (C_2 \times D_2) U\ (C_3 \times D_3)$

- Step 11: In order to estimate the delay duration, the fuzzy logic model performs a fuzzy composition matrix by taking the composition of the union matrices *T* and *V*, which are given in Figures (A.36) and (A.41), respectively. The composition matrix obtained is shown in Figure A.42.

Delay Duration

Frequency of Occurrence	3	4	5	6	7	Row Summation	Frequency Product
0	0.00	0.00	0.20	0.70	1.00	1.90	0.00
0.1	0.00	0.00	0.20	0.70	0.90	1.80	0.18
0.2	0.00	0.00	0.20	0.50	0.50	1.20	0.24
0.3	0.00	0.00	0.20	0.20	0.20	0.60	0.18
0.4	0.00	0.00	0.20	0.70	0.80	1.70	0.68
0.5	0.00	0.00	0.20	0.70	1.00	1.90	0.95
0.6	0.00	0.00	0.20	0.70	0.80	1.70	1.02
0.7	0.00	0.00	0.20	0.20	0.20	0.60	0.42
0.8	0.00	0.00	0.04	0.49	0.50	1.03	0.82
0.9	0.00	0.00	0.04	0.49	0.90	1.43	1.29
1.0	0.00	0.00	0.04	0.49	1.00	1.53	1.53

Figure A.42 Composition Matrix for Example Project: $T \circ V = \max \{\min [T(F,C), V(C,D)]\}$

• Step 12: The fuzzy logic model selects from the matrix shown in Figure A.42, a fuzzy subset for the delay duration. The last row in the matrix was selected because it maximizes the product of the row summation and its corresponding frequency of occurrence. Next, the fuzzy logic model calculates the probability of occurrence for each element of the delay duration using equation (3-41). Then, the fuzzy logic model uses equations (3-42) and (3-43) to estimate the values for mean, μ_D, and standard deviation, σ_D, of the delay duration. The following values are obtained:

- Probability of occurrence for each element of the delay duration:

  $P(D = 3)$ = 0.00
  $P(D = 4)$ = 0.00
  $P(D = 5)$ = 0.03
  $P(D = 6)$ = 0.32
  $P(D = 7)$ = 0.65

- Mean delay duration: μ_D = 6.63 weeks

- Standard deviation: σ_D = 0.53 weeks

The procedure to estimate delay impacts was implemented in the form of a computer program. This program was used to determine the duration of the delays presented in Table A.1. The delays affected activities Floors and Partitions, Roof, Electrical, and Mechanical. Tables A.16 to A.20 show the delay-sensitive attributes selected by the user to determine the duration of the delays that affected these activities. Table A.21 summarizes the mean delay durations and standard deviations obtained for each of the activities affected by delays.

Table A.16 Delay Sensitive Attributes for Floors and Partitions (Delay Type 2)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Large Very Small Small	Very Large Small Very Large
Subject to / requires design changes	High Average Low	Large Medium Small	Very Large Large Very Small

Table A.17 Delay Sensitive Attributes for Roof (1st Delay Type 3)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Medium Large Very Small	Large Very Large Small
Temperature	Bad Medium Good	Small Medium Medium	Large Medium Very Small
Sensitivity to Precipitation	High Average Medium	Large Large Medium	Very Large Large Small

Table A.18 Delay Sensitive Attributes for Electrical

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Very Large Medium Very Small	Very Large Large Large
Precipitation	High Average Low	Large Medium Very Small	Very Large Medium Small
Wind	High Average Low	Large Small Small	Very Large Medium Very Small

Table A.19 Delay Sensitive Attributes for Mechanical (1st Delay Type 2)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Large Medium Very Small	Very Large Large Very Large
Subject to / requires design change	High Average Low	Large Medium Small	Very Large Large Quite Small
Design complexity	High Average Low	Large Small Medium	Very Large Small Very Small

Table A.20 Delay Sensitive Attributes for Mechanical (2nd Delay Type 3)

Sensitive attributes	State	Frequency of occurrence	Adverse Consequences
Duration	Long Medium Short	Large Medium Small	Very Large Large Very Large
How equipment intensive	High Average Low	Large Medium Very Small	Very Large Large Small

Table A.21 Delay Durations

ID	Activity	Delay Duration Type 2		Delay Duration Type 3		Date of Occurrence
		Mean	Variance	Mean	Variance	
D	Floors / partitions			1.42	0.59	Week 13
E	Roof			4.25	0.84	Week 13
				3.00	0.87	Week 19
G	Electrical	6.63	0.53			Week 15
H	Mechanical	4.46	0.55			Week 15
				4.49	0.66	Week 20

A.4 Estimation of Triangular Membership Functions from Probability Density Functions

As described in Section 3.6, the outputs of the methodology explained in Section 3.5 are estimates of the mean value and standard deviation of the duration of a delaying event. The probability density function (PDF) of the delay duration is generated by the fuzzy logic model using the parameters obtained by this technique. The values of the PDF curve are then transformed by the fuzzy logic model into fuzzy membership functions, according to Dubois and Prade (1986). Figures A.45 to A.50 are graphical representations of the fuzzy numbers estimated from the delay duration PDF's derived in the previous section. (Refer to Table A.21).

Figure A.43 shows the activity duration PDF that corresponds to activity E, "Roof". This activity will be used to illustrate the application of the method. The parameters of the activity duration are: mean, μ_D = 4.25 weeks, and standard deviation, σ_D = 0.84 weeks. The values of the PDF curve are then transformed according to Dubois and Prade (1986) to obtain the membership function curve. Figure A.44 illustrates the transformation performed.

Referring to Figure A.44, the membership function obtained is bell shaped. In order to define the π-curve, it is necessary to determine the range parameters *a* and *c* (Refer to Figure 3.8). Parameter *a* corresponds to the mean delay duration, in this case *a* = 4.25. Parameter *c* is determined by calculating the area under the membership function that corresponds to the maximum value of the cumulative function, in this case *c* = 2.81. Since the area under the curve is one half of the range over which the function is defined, the bounds are determined as follows: *a* - *c* = 1.44 and *a* + *c* = 7.06. Referring

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to Figure A.44, it can also be seen that the membership functions of the values $a - c/2$ (2.84) and $a + c/2$ (5.66), is 0.5.

A triangular fuzzy number can be represented by the lower bound, the modal value, and the upper bound. The value for these parameters can be taken from those corresponding to the π-curve. Figure A.45 is a graphical representation of the fuzzy number obtained. As can be seen, the area of the fuzzy number is equal to ½(2.81 x 2) = 2.81, and it is equal to the area under the π-curve membership function. Table A.22 summarizes the total delays that occurred including delay Type, duration, nature (fuzzy or crisp) and date of occurrence.

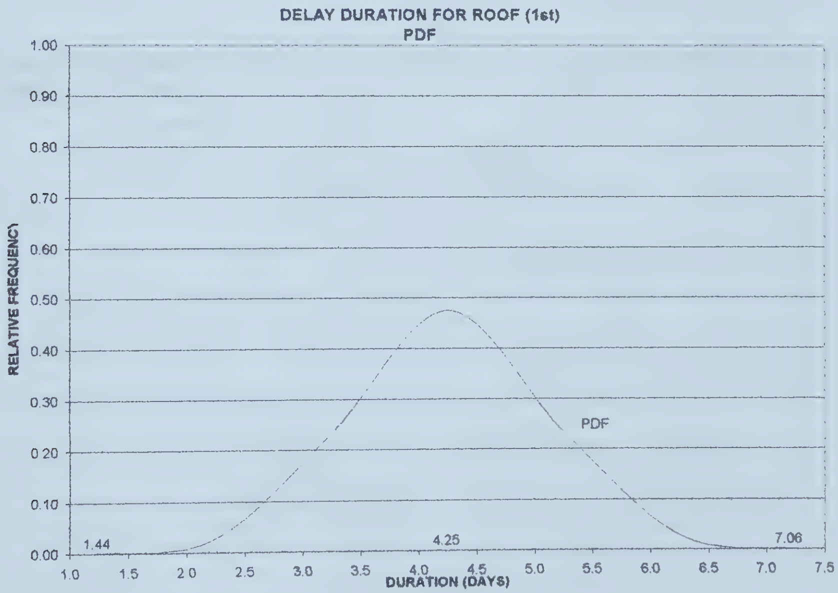

Figure A.43 Delay duration PDF for activity E, "Roof" (1st Delay)

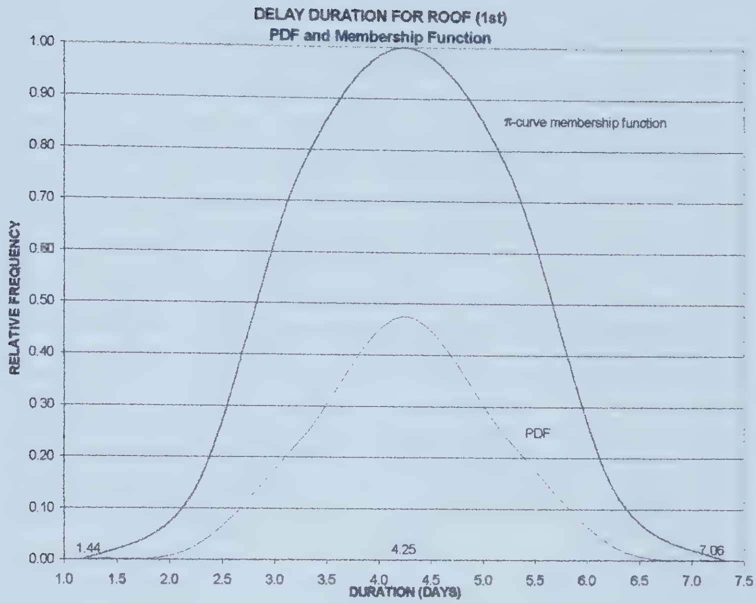

Figure A.44 Delay duration PDF, π-curve and Triangular membership functions for activity E, "Roof" (1st Delay)

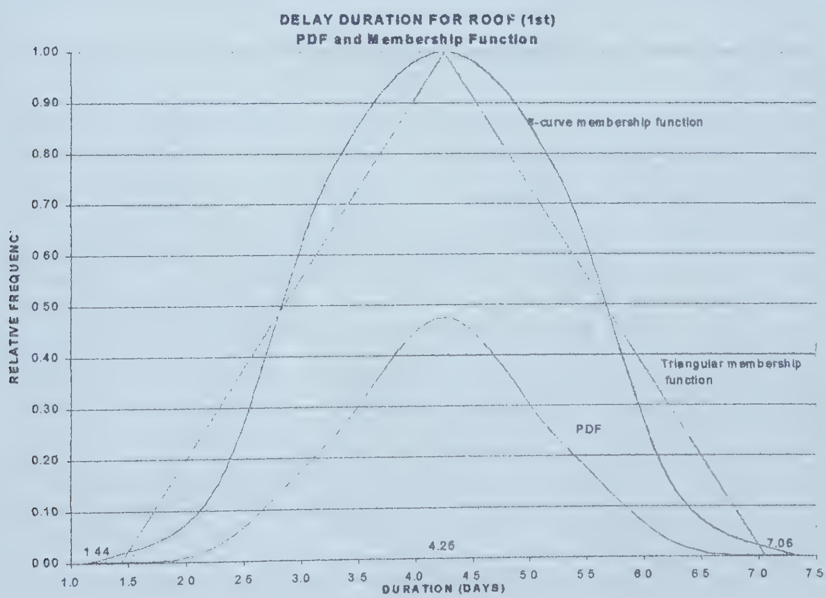

Figure A.45 Delay duration PDF, π-curve and Triangular membership functions for activity E, "Roof" (1st Delay)

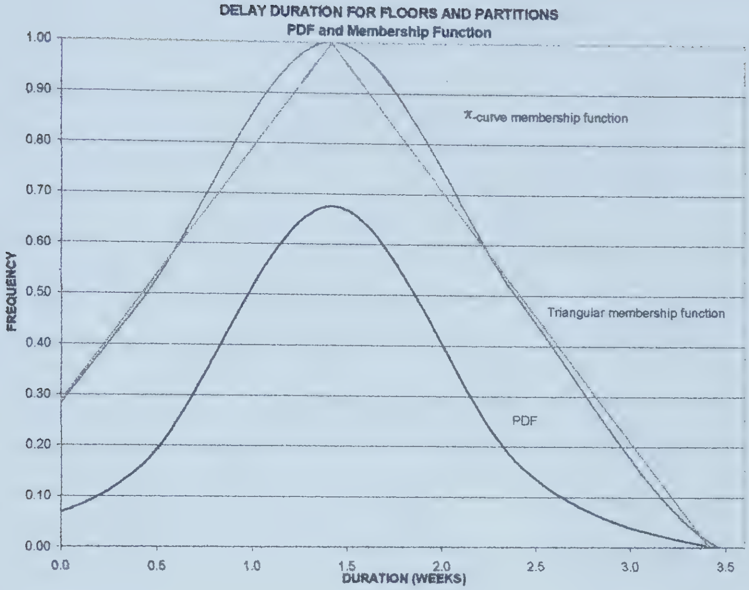

Figure A.46 Delay duration PDF's and Membership functions for Floors/Partitions

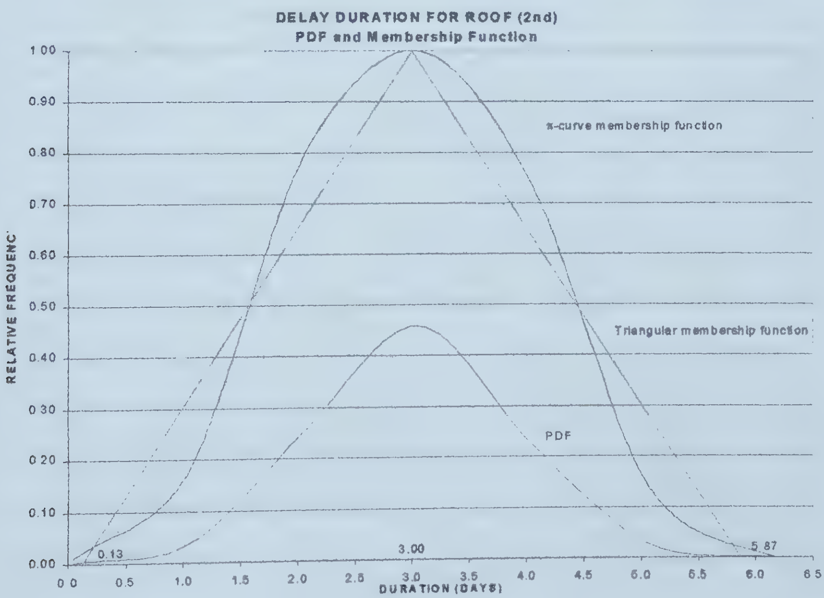

Figure A.47 Delay duration PDF and Membership functions for Roof (2nd)

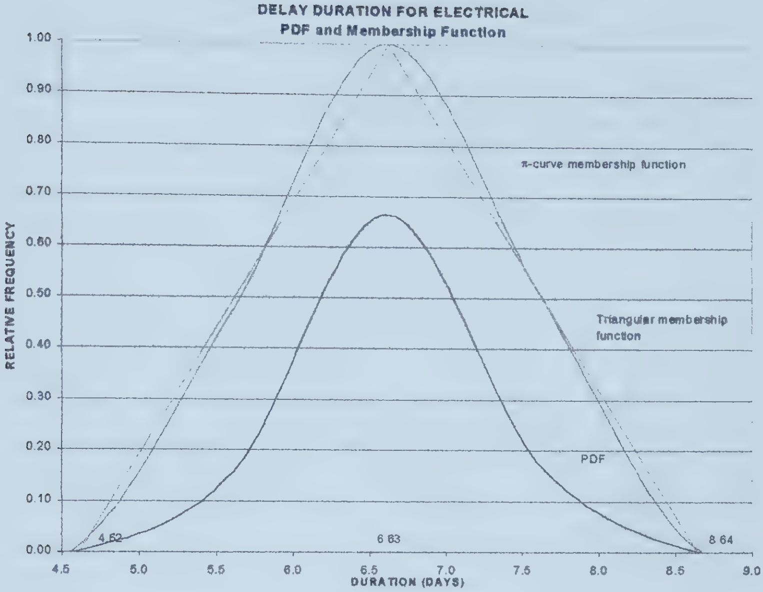

Figure A.48 Delay duration PDF and Membership functions for Electrical

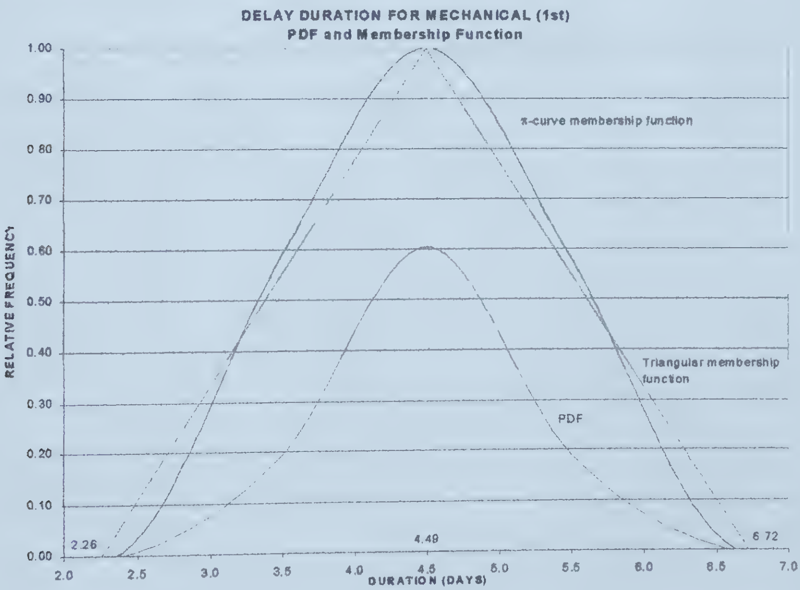

Figure A.49 Delay duration PDF and Membership functions for Mechanical (1st))

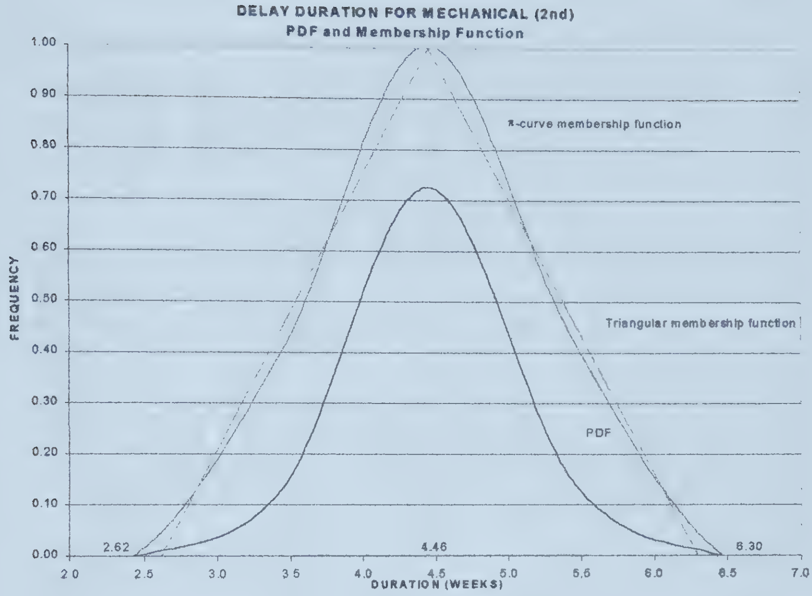

Figure A.50 Delay duration PDF and Membership functions for Mechanical (2nd)

Table A.22 Summary of Delay Characteristics for Example Project

ID	Activity	Delay Duration Type 1*	Delay Duration [weeks] Type 2			Delay Duration [weeks] Type 3			Triangular Fuzzy delay duration [weeks] Type 2 and 3	Date of Occurrence Type 2 and 3
			Crisp	Mean	Variance	Crisp	Mean	Variance		
A	Foundation		1			1			(1 , 1 , 1)	Week 3
						1			(1 , 1 , 1)	Week 6
B	Structural Steel	3	1						(1 , 1 , 1)	Week 7
C	Pour slab	4								
D	Floors / partitions	4					1.42	0.59	(-0.6 , 1.42 , 3.42)	Week 13
E	Roof	4					4.25	0.84	(1.44 , 4.25 , 7.06)	Week 13
							3.00	0.87	(0.13 , 3.00 , 5.87)	Week 19
F	Masonry	4								
G	Electrical	5		6.63	0.53				(4.62 , 6.63 , 8.64)	Week 15
H	Mechanical	5		4.46	0.55				(2.62 , 4.46 , 6.3)	Week 15
							4.49	0.66	(2.26 , 4.49 , 6.72)	Week 20
I	Interior finishes	12								
J	Painting	11								

A.5 Revised Activity Durations

Once the delay durations are assessed, the activity durations are revised to reflect the delays. Figures A.51 and A.52 illustrate the calculations employed on the procedure for the Activity E, "Roof". This activity has an original duration of three weeks. One week of normal progress is performed when a delay occurred on the activity. The progress date selected to perform a snapshot is the beginning of week 13, when the delay occurred. Since the date of the snapshot corresponds to the date of the occurrence of delays, the delay duration is not known with certainty. The model calculated the delay duration and is represented by the following triangular fuzzy number: (1.44, 4.25, 7.06). When the delay is projected to be completed, there are still two weeks of work to be performed.

Normal progress and remaining duration comprise the crisp portions of the activity duration. The portion of delay or nonproductive work is represented by fuzzy a number and thus is fuzzy. Figure A.51 illustrates the different portions that comprise the activity duration. Fuzzy addition is employed in order to quantify the different portions of activity duration and to determine the revised activity duration obtained after it has been impacted by a delay. Figure A.52 illustrates the calculations to determine the revised activity duration.

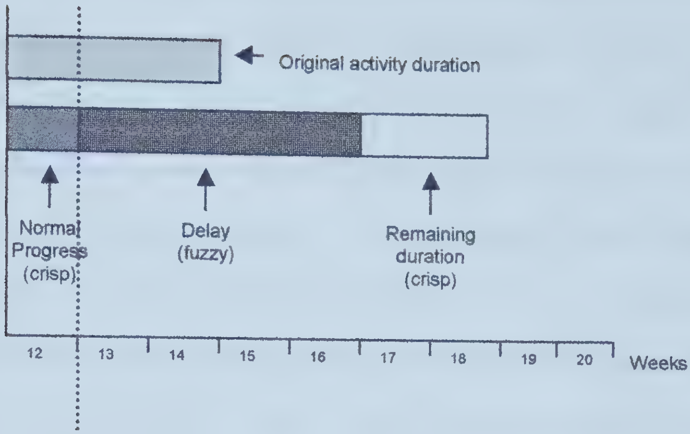

Figure A.51 Crisp and Fuzzy Portions for the First Revised Duration

Activity:

E Roof

			Triangular Fuzzy Numbers
Original duration:	**3**	**weeks**	
Normal Progress:	1	week	(1 , 1 , 1)
	Mean	Variance	⊕
Delay Type 3 (1st) :	4.25	0.84	(1.44 , 4.25 , 7.06)
			⊕
Remaining duration:	2	weeks	(2 , 2 , 2)
Revised duration in weeks:			**(4.44 , 7.25 , 10.06)**

Figure A.52 First Revised Duration of Activity E, "Roof

However, since the remaining work time is still eligible for additional impact, further interruptions to activity progress are also analyzed as they occur. It was determined that activity E, "Roof" will suffer a second delay approximately at the beginning of week 19. Figures A.53 and A.54 illustrate the calculations employed to determine the revised activity duration. Another snapshot was performed at the beginning of week 15, two weeks after the first delay occurred. Since the fuzzy logic model had determined that the delay duration of this delay was about A.25 weeks, this delay has not been completed yet. Since the date of the snapshot is previous to the date of the occurrence of the second delay, this delay duration is not known with certainty. The model calculated the delay duration and is represented by the following triangular fuzzy number: (0.13, 3.00, 5.87). Now, two portions of crisp duration and two portions of fuzzy delay duration comprise the project duration.

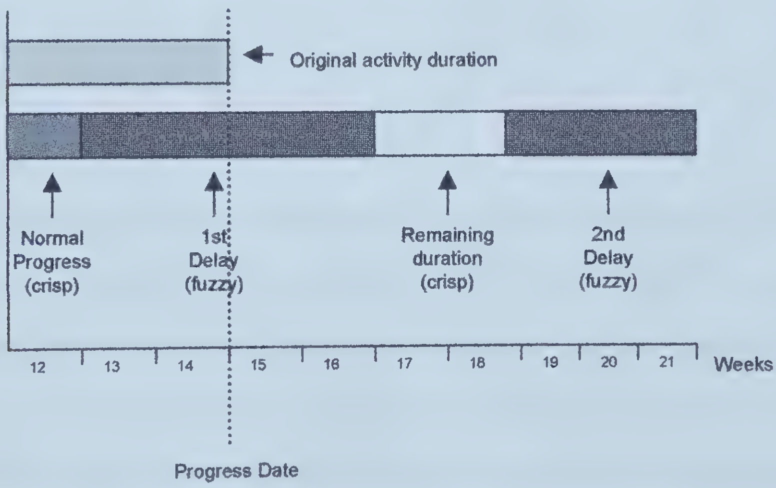

Figure A.53 Crisp and Fuzzy Portions for the Second Revised Duration

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[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

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Activity:

				Triangular Fuzzy Numbers		
E Roof						
Original duration:	**3**	**weeks**				
Normal Progress:	1	week		(1	, 1	, 1)
	Mean	Variance			⊕	
Delay Type 3 (1st) :	4.25	0.84		(1.44	, 4.25	, 7.06)
					⊕	
Remaining duration:	2	weeks		(2	, 2	, 2)
	Mean	Variance			⊕	
Delay Type 3 (2nd) :	3.00	0.87		(0.13	, 3.00	, 5.87)
Revised duration in weeks:				**(4.57**	**, 10.25**	**, 15.93)**

Figure A.54 Second Revised Duration of Activity Roof

The procedure just describe is applied to every activity in the project that experienced a delay. The results of these calculations can be observed in Figures A.6, A.10, and A.17, on Section A.2.

A.6 Forecast Progress at Completion

To illustrate the calculations used to update the schedule, the calculations performed on a selected activity (activity D, "Floors and Partitions") on the second snapshot, are shown. Section A.2.2. contains the schedule and all figures related to the calculations performed on the second snapshot. Figure A.11 contains all the CPM calculations performed on the second snapshot. In the forward pass calculations, FES_D takes the value of (11, 11, 11, 11) from the FEF of its predecessor (i.e., FEF_C in this case), using equation (3-59). The FEF_D can be calculated as (12.42, 14.42, 14.42,

16.42) by adding its duration (1.42, 3.42, 3.42, 5.42) to (11, 11, 11, 11), using equation (3-60).

Once the forward pass calculations are completed, the fuzzy duration of the project is set equal to the *FEF* of activity "Painting", i.e. (19.44, 22.25, 22.25, 25.06) weeks. This duration can be interpreted as approximately 22.25 weeks, with a definitive minimum time of 19.44 weeks and a definitive maximum completion time of 25.06 weeks.

For the backward pass calculations, the computation for the late times of each activity begins with the determination of its preliminary late finish (*PLF*) using equation (3-66). For activity *D*, the PLF_D takes the smallest *FLS* of its successors (i.e. activity *G* "Electrical"), which is (13.25, 15.25, 15.25, 18.06). $PLF^U{}_D$, can then be computed using PLF_D and equation (3-67) to be ($-\infty$, $-\infty$, 15.25, 18.06) weeks. The first step involved in the calculation of the PLF_D involves the comparison of the right spreads between the $PLF^U{}_D$ and FEF_D. The comparison shows that the right spread of $PLF^U{}_D$ is greater than that of FEF_D [i.e. (18.06 - 15.25) > (16.42 - 14.42)]. Accordingly, the fuzzy number *Y* can be calculated using the following equation: $Y = (f\text{-}d, f\text{-}d, f\text{-}d, f\text{-}d)$, as (1.64, 1.64, 1.64, 16.4). FLF_D is calculated using equation (3-69) and then the FLS_D using equation (3-70) to be (14.06, 16.06, 16.06, 18.06) and (12.64, 12.64, 12.64, 12.64), respectively.

Next, the criticality of project activities can be calculated. Figure A.12 shows the fuzzy durations, possibility measure, and agreement index for each path in the network of snapshot 2. The possibility measure were determined as the highest point in the intersection area produced by the critical paths and the project duration. The agreement indices were determined by calculating the ratio of the intersection area between the critical paths and the entire area of the project duration. Figure A.12 shows that critical

path 1 is clearly the only critical path and thus corresponds to the project duration (i.e. PM=1, AI=1). Paths 2 and 3 however can be considered as moderately critical, since about 50% of their path durations agree with the calculated fuzzy project duration. (i.e. the AI values are approximately 0.5).

At the activity level, Figure A.12 shows that activity *D*, "Floors and Partitions" is present on paths 2 and 3. Since path 2 is more critical than path 3, activity *D* takes its PM and AI from those of path 2 (i.e., PM = 0.84, AI = 0.72, as shown in Figure A.12). Figure A.13 contains the PM and AI values of each activity in the network, as well as the summation of PM and AI values. The cumulative degree of criticality of an activity is the summation of each possibility measure, and the summation of each agreement index for all the paths to which it belongs. The cumulative degree of criticality of activity *D* is comprised by the summation of PM values of paths 2 and 3 (i.e. 1.09), and by the summation of the AI values of paths 2 and 3 (i.e. 1.26). Activities that are present in a large number of paths in the network tend to have a higher cumulative degree of criticality that those common to a smaller number of paths. Activities *A, B, C, I, J* have the highest cumulative degree of criticality values because they are common to all paths in the schedule. The cumulative degree of criticality gives an indication of the possibility for creating a bottleneck that can affect the project schedule.

The approximate total float of activity *D* can be obtained by first calculating the geometric centroids of FLF_D and FEF_D using equation (3-85) and consequently substituting these values into equation (3-88). This yields 16.06 for FLF_D and 14.42 for FEF_D, and the total float can be calculated as 1.64 weeks (i.e. 16.06 - 14.42) (refer to Figure A.11).

A.7 Effects of Delays on the Schedule

To illustrate how the effects of delays on the schedule are analyzed in this model, activity D, "Floors and Partitions" in the second snapshot is selected. Section A.2.2. contains the schedule diagram and all figures related with the calculations performed on the second snapshot. Figure A.8 contains the bar chart for the second snapshot. It can be observed that activity *D*, "Floors and Partitions" suffered a delay at the beginning of week 13. Activity *D*, "Floors and Partitions" was previously a critical activity and the delay it suffered is Type 3. Concurrently Activity *E*, "Roof" that was previously a non-critical activity suffered a delay Type 3. This delay on a non-critical activity has the effect of delaying the project completion date due to the fact that the entire float available was consumed and did not absorb the effect of the delay. Activity *E*, "Roof" turned critical to the progress of the works and caused a shifting in the critical path (Refer to Figures A.5 and 4.9). Activity *D*, "Floors and Partitions" turned non-critical to the progress of the works even though it suffered delay, which has no effect upon the actual completion date of the works. This is due to the fact that the concurrent delay experienced by Activity *E*, "Roof" introduced float to activity *D*, "Floors and Partitions" and thus became non-critical. Table A.3 and Figure A.14 describe the effects of the delays suffered by the all activities in the second snapshot.

A.8 Consequences of Delays

The project manager of this project decided to take measures in order to diminish the cumulative effects of delays that project activities suffered. Activities *I*, "Interior Finishes" and *J*, "Painting", in the fourth snapshot are selected to illustrate how the project manager decreased the effects of delays on the schedule. Section A.2.4. contains

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the schedule diagram and all figures related with the calculations performed on the fourth snapshot. Figure A.22 contains the bar chart for the fourth snapshot. Figure A.23 contains the network diagram for the fourth snapshot. By comparing these two figures with Figures A.15 and A.16, respectively it can be observed that activities *I*, "Interior Finishes" and *J*, "Painting", were rescheduled by modifying their logic relationships. Also activity *J*, "Painting", was accelerated so that only half the time of its original duration is required. The project manager took these measures in order to modify the start and finish dates obtained by updating the schedule in snapshot 3 (refer to Figure A.18). This was done by modifying the information contained in the Projected and As-Built section of the as-built database, for activities *I*, "Interior Finishes" and *J*, "Painting", in the fourth snapshot. The schedule was recalculated based on the revised durations and logic indicated by the project manager. The results are shown in Figures A.22, A.23 and A.24.

A.9 Summary

In this chapter, a hypothetical example project was presented with the purpose of illustrating the fuzzy model components and calculations described in Chapter 3. The example project is a simplified house construction project consisting of ten activities. The project was originally scheduled to be completed on week 16. Four snapshots were performed at different points in time in order to update the schedule based on the occurrence of delays. The cumulative effect of the delays that affected project activities extended the project completion time to week 26. Therefore, as of the fourth snapshot, the project completion date slipped by ten weeks.

Project delays were categorized utilizing a cause/effect matrix that relates the causes of delays with the corresponding party responsible for them. Section A.3

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illustrated the methodology used to estimate delay durations using fuzzy sets and fuzzy relations. Section A.4 illustrated the procedure used to transform delay durations into triangular fuzzy numbers. Section A.5 explained how original activity durations are revised and increased. Section A.6 illustrated the method used to recalculate and update the schedule in terms of fuzzy early and late times. Section A.7 illustrated how the effects of delays on the schedule are dealt with in this model. Section A.8 described the measures taken by the project manager to minimize the overall effect of delays.

The next chapters present the data collection process and the analysis of a case study of an actual project that is analyzed using the fuzzy logic model.